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THE NATURE OF VOLCANIC ACTION.

By Reginald A. Daly.

With Five Plates.

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The Problem.

Volcanic action is the working of the extrusive mechanism which brings to the earth's surface rock-matter or free gas, initially at the temperature of incandescence. The mechanism involves the localization, opening, and shaping of the vent; the persistence of a vent as an open channel during seconds, days, years, centuries, or milleniums; the conditions for lava outflow, for gas and vapor outflow, and for the separation of gas or vapor from lava; the conditions leading to the periodicity of eruption at central vents; and those leading to chemical variations in the erupted magma.

Since the days of the Greek philosophers thousands of memoirs have touched upon this complex problem of terrestrial dynamics, but geologists are still looking for a generally acceptable solution. Within the last ten or twelve years the variety of new suggestions affecting the very core of volcanic theory has been, perhaps, as great as that of any previous decade. In the varying chemical affinities of water and silica for the bases of rock-matter at different temperatures, Arrhenius finds an essential condition of all vulcanism. He therefore attempts to support the time-honored hypothesis that the vapor of meteoric or marine water absorbed in plutonic magma is the prime motor in eruptions.[1] On the other hand, Brun holds that water is quite unessential to eruption of the first order, and he believes he can prove his thesis by actual analysis of the volcanic emanations.[2] Again, Chamberlin explains vulcanism as due to the extrusion of magmatic tongues, which, by tidal stresses, are slowly kneaded out of the deep interior of the otherwise solid earth.[3] In entire contrast to that hypothesis, Dutton has come to the belief that the indications are that most of the volcanic eruptions originate at depths between one mile and two and a half miles.[4]

[1] S. Arrhenius, Geol. Fören. i Stockholm Förhandl., **22**, 395–419 (1900).

[2] A. Brun, Archives des sciences physiques et naturelles, Geneva, février, 1909; février, 1908; novembre, 1906. Le Globe, octobre, 1907.

[3] T. C. Chamberlin and R. D. Salisbury, Geology, **1**, 632 (1906), and **2**, 104 (1906).

[4] C. E. Dutton, Volcanos and Radioactivity, 1906, p. 5 (Paper read before the National Academy of Sciences, April 17, 1906), published at Englewood, N. J.

Without further noting the divergences of recent views, it is clear that volcanic theory is in a disorganized state.

There is one patent reason for this conflict of opinion. The Vesuvian "steam-engine" and the geyser-like Stromboli have dominated European thought. Though living in a wilderness of waters, the brilliant Englishman in Hawaii, W. L. Green, concluded that water is not an essential agent in vulcanism, for he had lived many years meditating on the dry, or nearly dry, emanation from Kilauea.[5] Arrhenius, a physical chemist; Moissan, a synthetic chemist; Brun, an analytic chemist; Mallet, a civil engineer; von Buch, a Wernerian geologist; von Humboldt, a Wernerian who traveled greatly; Scrope, who built his philosophy on observations in the limited European field: Stübel, a specialist in the giant volcanoes of Ecuador; Tschermak, a mineralogist; Daubrée, an experimental geologist; Dutton, master of geological reconnaissance — each of these, and every other leader in volcanic study has been forced to think in terms of his intellectual environment. Each investigator has approached the many-sided problem with special training and experience, and many vulcanologists have shared the racial subjectivity which finds explosions, earth-shaking, and other surface events humanly so important as largely to control inductions on the theoretical side. During the last half-century the discovery and study of thousands of plutonic igneous masses have promoted the view that vulcanism is a subsidiary effect of intrusion. This thesis is emphasized and illustrated in the following pages, wherein the attempt is made to show its agreement with the essential facts known about volcanoes, ancient and modern.

A general working theory of vulcanism is here outlined. It has taken its full form directly as a result of the writer's studies in the Hawaiian Islands during 1909, but many of the chief conclusions are founded on his field-work in plutonic geology as well as in the geology of many ancient volcanic formations. The effort has been made to cover the more important literature of vulcanism, and as yet no facts therein stated seem to the writer to be irreconcilable with the theory, which, on the other hand, finds strong support in the great body of recorded facts. Many of the essential points in the following argu-

[5] "Water in a rainy district gets to the hot rocks in all sorts of ways, about which there need be little mystery. All this steam seems to have no further connection with the forces concerned in the action of the lavas in Kilauea, than the vapors which arise from the body of a hard-worked horse, when a shower of rain has fallen on him, have with the force he exerts in drawing his load." — W. L. Green, Vestiges of the Molten Globe, Part II., p. 82, Honolulu, 1887.

ment are by no means new. The principal reason for adding this paper to the already overburdened literature on volcanoes is that it attempts to coördinate the accepted principles of vulcanology with each other and with the truths of plutonic geology. Whether or not the actual result is to meet with favor among geologists, the writer feels certain that the synthetic ideal in vulcanological study has not been actively pursued in anything like its just measure. That this pursuit necessarily involves some speculation concerning the earth's interior is not a valid objection to the undertaking. The earth's interior is no more invisible than is the interior of a molecule. The sanction for modern chemistry has become as strong as it is because philosophical chemists have speculated about the invisible, intangible, and unweighable. Similarly, to be more productive than it is, geology must become more speculative. In this there is danger if the hypothesis is founded only on the facts met with in the individual worker's experience; there is little danger, but great promise of fruit, if the speculation is synthetic and regards all the published facts.

During the preparation of this paper the writer has been greatly aided by discussion of many points with his colleagues, Professor W. C. Bray, T. A. Jaggar, Jr., G. N. Lewis, and A. A. Noyes of the Massachusetts Institute of Technology, and also with Professor H. N. Davis, Professor L. S. Marks and Dr. P. W. Bridgman of Harvard University, and Professor A. C. Lane of Tufts College. To these gentlemen the writer's sincere thanks are due; he alone, however, must bear the responsibility for the form and substance of the paper. He wishes further to express special thanks to the Director and chemists of the United States Geological Survey, who have supplied two of the chemical analyses noted in the text; to Mr. H. E. Wilson, of Hilea, Hawaii, who has furnished one of the photographs here reproduced; and to Mr. Walter E. Wall, Government Surveyor of Hawaii, who has extended many courtesies to the writer, and gave him permission to copy many manuscript maps used in the assembling of some of the facts on which this paper is based.

Abyssal Injection.

Surveys on each of the continental plateaus have already shown that the average rock of the plateau's basement (pre-Cambrian terrane) is, chemically speaking, of granitic composition, with a silica-percentage not far from 70. Notwithstanding the vast erosions of many geological periods, this terrane is, in places, known to extend downward several kilometers even at the present time, and it is a reasonable inference, contradicted by no fact yet discovered, that the acid complex has, gen-

erally, a minimum depth of many kilometers. Upon its back each of these acid continental plateaus carries a sedimentary pellicle, locally increased to the imposing thickness of geosynclinal prisms. (See Figure 1.)

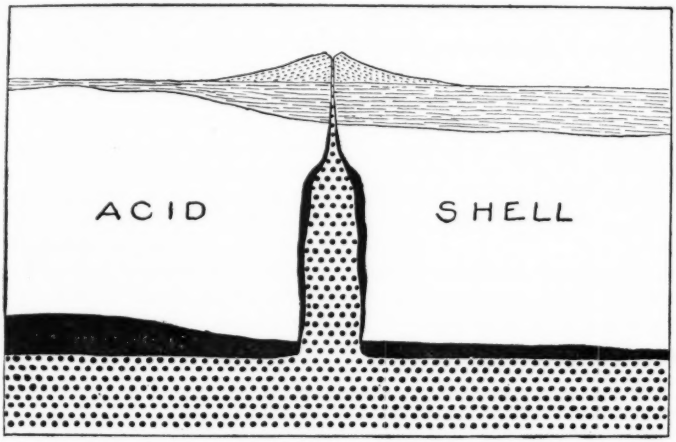

FIGURE 1. Diagrammatic section of the earth-shells, showing abyssal injection and accompanying central eruption. The broken lines below the cone represent a geosynclinal prism merging into sediments of more usual thickness. Solid black represents solidified matter of the basaltic substratum, the broad horizontal band indicating the part of the substratum crystallized since an early pre-Cambrian period. Heavy dots represent fluid matter of the substratum, in position after the abyssal injection has partly crystallized (along its walls). Scale given by height of cone, assumed as projecting 5 kilometers above the plain of sediments.

Most volcanic rock is of basaltic or andesitic composition, and it is clear that such material has not been derived from the mere liquefaction of the basement terrane, or of the sedimentary veneer, or of both together. The great bulk of the world's lava is *exotic*. It has *penetrated* the basement terrane and the sedimentary shell without absorbing these in large proportion. We thus seem driven to believe in *abyssal fissures*, opened in the earth's outermost shells for the passage of the molten rock.

By analogy such abyssal injection may be assumed as the preliminary stage of Pacific vulcanism, although there is much to be said for the view that the primary acid earth-shell is lacking, or else is very thin,

over most of the area covered by that ocean. For example, geodetic results seem to suggest that the Pacific sediments rest, more or less directly, on a terrane whose average density is nearer the density of crystallized basalt than that of granite or common gneiss.

In the case of the greater lava-fields, the abyssal fissures have been prolonged, as true fissures, to the surface; there a leading condition of extrusion is probably the simple hydrostatic adjustment of magma to a breaking earth-crust. Most central eruptions have occurred in localities where emitting fissures are not visible. In emphasizing this fact some geologists have been disposed to deny that fissuring of the crust is a prerequisite of vulcanism. Their reasoning is strong so far as the actual opening of many vents is concerned, and one result has been to sharpen the eyes of vulcanologists as to field relations. But we may agree with Supan that "one should not throw out the baby with his bath-water." Though a vent, for the last few hundreds or thousands of meters, may have been opened by explosion or by other means than simple fissuring, a fair study of geological maps shows the existence of strong abyssal fissures beneath most of the volcanic piles which are not visibly located on surface fissures. Obviously, an immediate tendency of volcanic action is to cover such feeding fissures. Yet their existence is to be inferred from the group alignment of the greater cones. Such is, of course, the traditional explanation of groups like those of the American Cordilleras, of the Hawaiian series, the Samoan series, or the Antillean series. Some clusters of vents show no definite alignment; instances like the "embryo" volcanoes of Suabia will be discussed on later pages.

We may, therefore, assume abyssal fissuring and magmatic injection to be the *essential preliminary* to vulcanism, as it is, indeed, to all igneous action. Probably most vulcanologists have made the same assumption, but the literature of vulcanism nowhere contains a full statement of some of the chief theoretical consequences of the assumption. Some authors, either expressly or tacitly, refuse to believe in the principle, but their arguments against it have never been sufficiently supported by the facts of structural and areal geology. The matter is so fundamental that it has here been duly stated; it may savor of a truism to many working geologists.

Conditions of Abyssal Injection.

The principle may be accepted, though the circumstances permitting of injection at depths of ten, twenty, or more kilometers are not yet completely understood. This much more difficult subject has been

speculatively considered by the writer in a paper published in 1906.[6] Therein the general result of the work of Reade, Davison, Fisher, and G. H. Darwin, on the stresses produced in the earth through cooling, was assumed as true. A superficial shell of compression is separated from a much thicker underlying shell of tension, by a level of no strain. The tensions of the lower shell and the failure of complete "compressive extension" in that shell furnish the conditions favoring magmatic intrusion into the shell. The writer's earlier statement (page 204 of the paper referred to), that laterally-confined rock-matter grows vastly more rigid with increase of pressure, has been recently corroborated in striking fashion by Adams and Bridgman in their respective high-pressure experiments. Adams shows that, with lateral support at high pressure, the normally weak mineral, fluorite, became less plastic than hard steel at ordinary pressure.[7] P. W. Bridgman (verbal communication) has proved that under external hydrostatic pressure amounting to 24,000 atmospheres, the cavity of a sealed glass tube is not closed, even after prolonged application of such enormous force. In an actual test, a tube, having undergone a hydrostatic pressure of 24,000 atmospheres — corresponding to the weight of more than eighty kilometers of the earth's crust — for a period of three hours, was removed from the press and was found to have undergone no sensible change in size or form. These experiments seem to sustain the view that at least the upper, cooler part of the shell in which tension is developed on account of the cooling of the earth, is not kept fully and continuously condensed by the weight of the overlying shell. On the contrary, the shell of tension may be capable of considerable condensation, which awaits, as well as permits of, the periodic injection of liquid matter from the substratum. This is also the conclusion of Lane, expressed in his highly suggestive paper on the "Geologic Activity of the Earth's originally absorbed Gases," where he has considered the mechanics of abyssal fissuring.[8]

In general, the injections must find difficulty in passing beyond the level of no strain, which is only a few kilometers below the surface of the planet. In the cases where the magma does succeed in penetrating the shell of compression, volcanic action ensues.

Since the speculation is not vital to the argument of the present paper, it will not be further reviewed. It may be noted that the same

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[6] R. A. Daly, Abyssal Igneous Injection as a Causal Condition and as an Effect of Mountain-building. Amer. Jour. Science, **22**, 195–216 (1906).

[7] F. D. Adams, Jour. Geol., **18**, 500 (1910).

[8] A. C. Lane, Bull. Geol. Soc. America, **5**, 269 (1894).

general conception has been independently stated by H. J. Johnston-Lavis, one of the world's most experienced students of volcanoes. Only quite recently has the writer found that he had been anticipated by Johnston-Lavis in the root idea, as expressed in brief notes published in the Geological Magazine.[9] It is a source of genuine satisfaction to find a fellow adventurer in an almost pathless field of investigation, and, yet more, to find in that companion a distinguished specialist.

The Substratum.

Similarly, the writer has found that he has been anticipated in the view that the heat-bringer in all Paleozoic and later igneous action is a general basaltic substratum underlying the shell of tension.[10] The essential point was stated by Cotta on page 78 of his "Geologische Fragen," published in Freiberg in 1858, and by W. Lowthian Green on page 61 of his "Vestiges of the Molten Globe," Part II, published in

[9] **17**, 246 and 344 (1890). A fuller statement by the same author appears in the Geological Magazine, **36**, 433 (1909).

[10] Cf. R. A. Daly, Amer. Jour. Science, **15**, 294 (1903).

The writer is clearly conscious that this assumption of an uncrystallized general substratum conflicts with the planetesimal hypothesis of the earth's origin, as stated by Chamberlin. Whatever be the mode of assemblage for the earth's materials originally, it is extremely difficult to accept the view that, when the planet approached its present size, it could have avoided a stage where it was molten all over the surface. Lunn's temperature-depth curve (Chamberlin and Salisbury's "Geology," 2d ed., **1**, 564, 1906) for the earth, computed on the accretion hypothesis, shows temperatures of from 10,000° to 20,000° C. in the interior. Since, on the hypothesis, the mode of accretion afforded a very heterogeneous mass at the beginning, there must have been a gravitative readjustment of the materials rendered fluid by the high temperature of the interior. The less dense matter, rising from great depth, would bring to the surface a large proportion of its enormous heat-content, ultimately fusing a surface shell of great depth. In other words, the earth-furnace imagined by Chamberlin and Lunn would melt its own walls.

Another serious objection to the hypothesis that the earth has been largely solid (crystalline) throughout its history is the fact that each of the planets, Jupiter, Saturn, Uranus, and Neptune, has a density appropriate to a gaseous condition and to very high temperature even in the surface shell. Again, if the moon were never fluid at the surface, its matter has been fluid very close to that surface; every square meter of its visible surface seems to have witnessed igneous action. So far, the published statement of the planetesimal hypothesis has not discussed the earth's history in terms of the facts known about its fellow members in the solar system. Since both the gas-nebula and planetesimal-nebula hypotheses seem to demand an incandescent, molten stage for the earth, the present writer is inclined to doubt that the geologist, for most of his thinking, needs a decision as to the truth of either hypothesis. That is a matter for cosmogony and astrophysics.

Honolulu in 1887. Each of these books first became accessible to the writer in 1909. It is certainly a pity that the second part of Green's work is not more generally known. The book is almost as remarkable a contribution to the philosophy of vulcanism as Part I, on the Tetrahedral Theory of the Earth, is important in cosmogonic philosophy. With the advance of geologic exploration, the arguments for a universal basaltic substratum are to-day more convincing than ever. For the sake of brevity these arguments will not here be fully presented, though some of them are mentioned in the sequel.

It will further be assumed that the known temperature gradient may roughly indicate the depth (estimated at 40 kilometers) at which the basaltic substratum is actually or potentially fluid. Many writers have independently arrived at nearly equivalent estimates for this depth. At such depth the internal friction may be so increased by the pressure that the substratum almost perfectly resists deformation by the quickly acting tidal forces.[11] This assumption in no way excludes the possibility that the substratum basalt is a true, non-crystalline fluid, and that a powerful force, slowly applied (on the principle of stress differences), could force this highly viscous fluid into the solid crust. As the fluid rises, its viscosity must fall directly with the lessened pressure, from a possible initial value of perhaps many millions of millions of times that of water to that of less than fifty times the viscosity of water, when the fluid reaches the earth's surface.[12]

Some Direct Consequences of Abyssal Injection.

The estimate of 40 kilometers for the average depth of the surface of the substratum may be wide of the mark, but it will serve as the numerical basis for a statement of certain immediate effects of injection.[13]

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[11] Herglotz has recently concluded that a planet stratified according to density must resist tidal deformation better than would the homogeneous planet assumed by Lord Kelvin. G. Herglotz, Zeit. für Math. u. Phys. **52**, 275 (1905).

[12] Becker computes the viscosity of a Hawaiian lava flow (which was by no means the most fluid already observed) as no more than sixty times that of water. G. F. Becker, Amer. Jour. of Science, **3**, 29 (1897).

[13] Perhaps the surface of the substratum is as deep within the earth as the limiting depth of isostatic compensation. In the second of his notable memoirs concerning the figure of the earth and isostasy, Hayford states that the most probable value of this limiting depth, for the United States and adjacent areas, is 122 kilometers, if it be assumed that the isostatic compensation is uniformly distributed with respect to depth. See page 77 of his "Supplementary Investigation in 1909 of the Figure of the Earth and Isos-

First, basaltic magma, rising from such depth nearly to the earth's surface, must undergo an average expansion ranging between 1.5 and 6 per cent.[14] A small part of this expansional energy may be directly available for opening fissures in the shell of compression, with consequent extrusion at the surface or development of laccolithic or other bodies within that shell.

Secondly, some superheat might be expected in each thick abyssal injection, at levels where the pressure is much less than the 11,000 atmospheres of the original substratum level. The conditions for the superheat have been briefly discussed in a previous paper.[15] Superheat in large abyssal injections means power of assimilating the wall rocks either marginally, or through magmatic stoping (forming syntectic magmas); the batholithic type of intrusion results. Thin abyssal injections, rapidly chilled, are relatively or absolutely incapable of such solution of foreign material; those injections form the other great class, typified by ordinary dikes. Each of these types is capable of developing offshoots of the laccolithic, chonolithic, or sheet order, so that satellitic injections of primary basalt or of syntectic matter are formed. This simple but necessary division into assimilating and non-assimilating injections is of first-class importance in volcanic theory, and underlies the reasoning of the present paper.

Thirdly, magma which has been forced from the substratum level to levels where the pressure is 10,000 atmospheres less, must have completely altered conditions of equilibrium for the juvenile gases. These include hydrogen, sulphur gas, carbon monoxide, carbon dioxide, chlorine, nitrogen, and other gases, elementary or in combination. The theory of physical chemistry indicates that the dissolved volatile constituents must, in such a case, slowly diffuse upward, in order to reestablish equilibrium. There is thus a tendency to saturate and then supersaturate the upper part of the magma with juvenile gases; if by the mere change of pressure the magma is supersaturated with one or more of the gases, bubbles must form and these must slowly rise. If

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tasy," Coast and Geodetic Survey, Washington, 1910. If the top of the liquid (non-crystallized) basaltic substratum were at a depth as great as 122 kilometers, this change in premises would make no essential difference in the argument of the present paper. It may be noted that John Milne (Nature, **86**, 124 (1911)), using Rizzo's results in studying the velocity of the earthquake waves which were recently so disastrous at Messina, has estimated the thickness of the earth's "crust" to be 44 kilometers.

[14] See Amer. Jour. Science, **22**, 201 (1906).

[15] Amer. Jour. Science, **26**, 33 (1908). Cf. J. Joly, Radioactivity and Geology, London, 1909, pp. 103–109, where there is an important discussion of one phase of this subject.

the injected body is tightly roofed, the gases continue to rise until the growing gas-tension at the upper levels stops diffusion.

Genetic Classification of Volcanic Gases.

It will conduce to clearness if a brief statement is here made as to the absolute necessity of distinguishing the different classes of volatile materials which are associated with igneous activity. These fluids are either *magmatic* or *phreatic*.[16] Phreatic fluids are of atmospheric or oceanic origin, and include *vadose* waters, and also those which Lane has called *connate* (contemporaneous) waters, because trapped in sediments at the time of their deposition. As indicated by Suess, explosions due to the heating of phreatic fluids by intrusive magma have occurred without the ejection of true lava, either fluent or pyroclastic.

Magmatic fluids are those actually dissolved in magma or emanating therefrom. Those of primary origin and reaching the earth's surface for the first time are of the *juvenile* class. The magmatic fluids of secondary origin, that is, those absorbed from country-rock formations, have been called *resurgent*.[17] Resurgent fluids may enter the magma either as constituents of assimilated country-rock or by independent solution.

Although only magmatic fluids are important in the present connection, it is useful to review, in tabular form, the whole group of gases and vapors which are engaged in volcanic and subvolcanic activities.

Magmatic fluids (volcanic; internal).	Juvenile	Emanations directly from abyssal injection.
		Emanations from primary solid abyssal country-rock.
	Resurgent	Vadose and connate fluids absorbed in the syntectic process.
		Vadose fluids absorbed independently of rock assimilation.
Phreatic fluids (subvolcanic; external)		Vadose.
		Connate.

The resurgent fluids may possibly do something toward keeping a vent open, but their volatilization means the partial lowering of temperature in the magma, so that their abundance in a conduit implies

[16] Cf. E. Suess, Das Antlitz der Erde, Bd. 3, 2te Hälfte, Wien and Leipzig, 1909, p. 655.

[17] R. A. Daly, Amer. Journ. Science, **26**, 48 (1908).

a certain "damping of the fires" already accomplished. In basaltic volcanoes assimilation of the normal, acid crust-rocks has evidently not been important; at such vents the juvenile emanations are clearly in control from beginning to end of each volcano's history. This statement does not conflict with the fact that resurgent water, either vadose or connate with sediments, is often responsible for the explosions at basaltic and other volcanoes. The clearing-out of the explosion funnel, which is always shallow and superficial, is not so vital to continued activity as the preservation of fluidity in the magma of the conduit.

Phases of Volcanic Action.

According to the views expressed in modern text-books of geology, the emission of incandescent matter at the earth's surface takes place either in the form of fissure eruptions or in the form of central eruptions. The writer believes that a third method should be entertained as a possibility, namely, by the partial or complete foundering of batholithic roofs. The relation of each of these three phases to abyssal and satellitic injection may now be sketched.

Fissure Eruptions (Massive Eruptions, Plateau Eruptions).

The regional or greater lava-floods known to have emanated from simple fissures in their underlying terranes range in date from the pre-Cambrian to the present. Without exception they are, chemically, of basaltic composition. As we have seen, such magma must be exotic. It is a type of lava (extrusive magma) to which a secondary origin cannot be theoretically attributed. Its abundance, its occurrence in every continental and oceanic area, and its field relations to the other chemical types of magma, all point to the derivation of the plateau basalt from a general substratum. Each flow thus represents an effusion from an abyssally injected body which has not been modified by assimilation of the earth's acid shell or of the sedimentary veneer. But the very low original slopes of the flows (very often inclined at less than one degree to the horizontal plane) and their correlative great lengths, show that the basalt of fissure eruptions is notably superheated. Such temperature is appropriate to assimilation.

That solution of pre-Cambrian gneisses or of other rocks has generally not taken place in sensible amount during fissure eruption must have either of two meanings. It may mean that the various abyssal injections underlying such a lava-field are narrow, with widths to be measured in meters or tens of meters, but not in thousands of meters; or the failure to assimilate may be due to special rapidity of injection

with simultaneous extrusion, for solution of foreign rock must take considerable time. The observed average size of the feeding channels (dikes) in the great lava-fields of the western United States, of Northwestern Europe, of India, and elsewhere, corresponds with the former conclusion. The Icelandic flow of 1783 and the nature of the individual basaltic flows in every prehistoric lava-field, show or suggest that each extrusion has been rapid. The controlling condition for the lack of assimilation is probably the narrowness of the abyssal injections, at least in the part traversing the sedimentary and acid shells of the earth.

The effusion of a basaltic flood is usually ascribed to the mere squeezing out of the magma from beneath a cracked and sinking earth-crust. Yet some force may also be available from the expansion of the substratum material as it rises to levels of enormously lessened pressure. This expansion is of two kinds; — that of the lava regarded as bubble-free, and that of the gases separated from it in bubble form. If the expansive energy of the liquid proper is not all expended in driving asunder the walls of the injected body, some of that great force is available for extrusion. As magma nears the surface, the separation of the dissolved gas must still further increase the volume and tend to cause outflow at the surface. The relative importance of these three conditions for extrusion is by no means apparent, though the writer believes that the expansional energy of the injected *liquid* should have more attention than it has had in general treatises on igneous action.

The fact that the great bulk of visible igneous rock is intrusive, and the related fact that most of the larger Paleozoic and later injections have not extended to the surface, suggest that the upper part of the earth's crust has long been comparatively difficult of penetration by abyssal magma. It seems fair to hold that a leading cause of this relative impenetrability is the state of compression in the outermost shell of the crust. This compressive stress is relieved by an orogenic paroxysm. After each paroxysm, tensions in the same shell are produced by the cooling of the rocks which had been heated by shearing. For a double reason, therefore, fissure eruptions should be more numerous and of greater volume in periods subsequent to strong mountain-building. This expectation is fairly matched by the facts of geological history, as shown in the accompanying table.

Locality.	Date of Fissure Eruption.	Preceding Orogenic Period.
Lake Superior District.	Keweenawan.	Close of the Animikie.
Rocky Mts. at 49th Parallel.	Middle Cambrian (?)	Early Middle Cambrian (?)

Locality.	Dale of Fissure Eruption.	Preceding Orogenic Period.
British Islands.	Carboniferous.	Devonian.
Appalachian Mts.	Triassic.	Close of Paleozoic.
Deccan, India.	Cretaceous (or early Tertiary ?).	Late Triassic (also later?).
Great Rift, Africa.	Cretaceous (Kaptian series).	" " " "
Washington State.	Eocene (Teanaway basalt).	Close of Laramie.
N. W. Scotland.	Oligocene (Lower Miocene).	?
Iceland.	Miocene.	?
Washington State.	Miocene (Yakima basalt).	Close of Eocene.
Great Rift, Africa.	Miocene (?)	Tertiary (Alps, etc.).
Great Basin, U. S. A.	Pliocene.	Miocene.
Snake River, Idaho.	Pliocene.	Late Miocene.
Hauran, Syria.	Pliocene.	Tertiary.
Iceland.	Pleistocene and Recent.	Tertiary.

Eruption through Local Foundering.

Narrow abyssal injections, like the average dike located near the earth's surface, will not be expected to show evidences of extensive assimilation of wall-rock, except at levels deeper than those which can be exposed by crustal deformation and erosion. If the width of the injection falls below a certain critical value, the magma is chilled too rapidly to permit of marginal solution or of stoping. If the width exceeds that critical value, the molten or magmatic period is prolonged and absorption of the country-rock by both methods may become important. Other conditions being alike, the critical width where the injection cuts the gneissic pre-Cambrian shell is doubtless somewhat greater than it is where the injection cuts the more hydrous, average sedimentary terrane. But in all cases, the minimum width for abyssal injections which have absorbed large masses of foreign rock, is to be measured in hundreds of meters, if not in kilometers. Abyssal injections of greater volume are believed by the writer to work their way upward, for hundreds or thousands of meters, by absorption of the country-rock. The molar-contact absorption may be directly solutional, or directly mechanical, i. e., by stoping (followed by solution of the sunken blocks in depth). The evidence for assimilation, either marginal or abyssal, is generally masked by that drastic differentiation

which is to be expected in large bodies of syntectic magma. This, in brief, seems to be the essence of batholithic intrusion. A batholith is an abyssal injection originally endowed with sufficient thermal energy (size) to enlarge its chamber through incorporating roof and wall rocks. The lower and greater part of its chamber is formed by simple dike-like injection along a widening abyssal fissure. The upper part, which is generally the only part exposed by erosion, has been opened by the activity of the magma itself. The average batholith, at exposed levels, is granitic because granite represents the stable and least dense differentiate of the average syntectic.

The integrity of the batholith's roof is evidently threatened in two ways. It is thinned during the process of absorption of the roof-rock by the molten magma. The latter might work its way to the surface through piecemeal stoping, which might continue until a large area of the batholithic roof has disappeared. On the other hand, it is also possible that part or all of the roof should, under special conditions, founder *en masse* in the less dense magma. In either case true volcanic action is produced. Such wholesale or piecemeal foundering would not fairly be called simple fissure eruption, though it might be accompanied by lava floods emitted from fractures in the roof-rock surrounding the foundered area. The level surface of the lava in the area of foundering would, in form, resemble a plateau (fissure) eruption, but the lava would here be generally liparitic rather than basaltic, as in the great majority of plateau eruptions. Moreover, the liparite would form a continuous mass merging downwards into granite, and thus not a series of superposed distinct flows. According to the topography, the lava of the foundered area might flood valleys outside that area. If the hydrostatic adjustment were accomplished in stages, it would cause successive, superposed flows in the valleys. (See Figure 2.)

Needless to say, the field evidences do not favor the idea of foundering in the case of many, perhaps most, Paleozoic and later batholiths. These bodies must be regarded as truly plutonic, according to the orthodox creed. Yet it is expedient to entertain the hypothesis in explanation of the field relations of some pre-Cambrian batholiths as well as those of a few younger masses.

In the first place, the evidence of local foundering in the past is in special danger of being obliterated. The glassy or scoriaceous phase of the "batholith" will necessarily be eroded away before the granitic phase can be exposed. The liparitic phase need extend to a depth of no more than a few hundred meters, where it would rapidly merge into the holocrystalline phase. Therefore, comparatively little time would

be required to remove the original surface phase. The geologist studying the erosion surface might have no inkling that the "batholith" had not been completely covered by a roof of country-rock. The former existence of a roof cannot be assumed simply because a "batholith" has a holocrystalline structure.

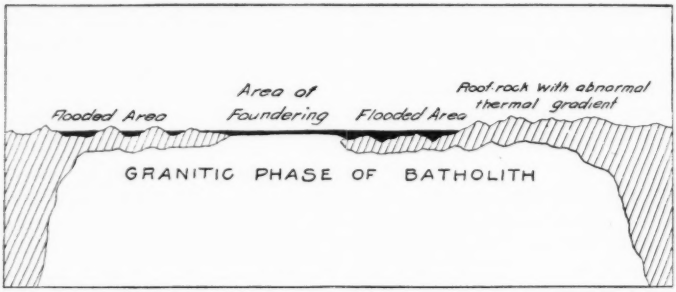

FIGURE 2. Ideal section of a district of batholithic foundering. Length of section assumed, for example, as 60 kilometers.

Blue Hills, Massachusetts.

The relations of the granite, quartz porphyry, and aporhyolite of the Blue Hills complex, near Boston, Massachusetts, to each other and to the Cambrian slate which forms the country-rock of the intrusive, suggest at least that the batholithic roof was very thin. Crosby describes two large areas of the aporhyolite (felsite) with the characters of both intrusive and effusive magma. He favors the view that these bodies are very thick surface flows of the ordinary type, though he states the alternative view that the aporhyolite represents the intrusive, latest phase of the batholithic magma.[18] The present writer believes that, in this case, the hypothesis of partial roof-foundering is worthy of a competitive place in a full discussion. The belief is founded on actual acquaintance with only a limited part of the observable field relations, and it is offered merely as a preliminary suggestion.

Glen Coe, Scotland.

The noteworthy paper of Clough, Maufe, and Bailey on "The Cauldron-subsidence of Glen Coe," illustrates a case where part of a

[18] W. O. Crosby, The Blue Hills Complex. Occasional Papers of the Boston Society of Natural History, **4**, 385 (1900).

batholith's roof has sunk along peripheral faults. As the sinking progressed, the magma was squeezed up, following the faults on nearly every side of the sunken area. If the faulting had progressed still further, it seems inevitable that foundering would have occurred. In fact, the authors give a synthetic diagram which implies foundering on an enormous scale, though in no instance is the sinking crust-block shown as having extended to the earth's surface.[19]

Yellowstone National Park.

The possibility that foundering has played a part in comparatively recent vulcanism, first became clear to the writer on a journey in the Yellowstone Park. (See Figure 3.) The great rhyolite plateau, the largest known on the earth, is cut by canyons reaching 600 meters in depth. The canyon-walls of the Madison and Bechler rivers show that, for nearly or quite this depth and for very great areas, the rhyolite is massive and is not divisible into a number of distinct flows, as is characteristic of fissure eruptions and central eruptions. The rhyolite extends downward, below the river-levels, to unknown depths.[20] Does it merge, directly beneath, into the true granite of a batholith?

Part I of the government survey Monograph is, unfortunately, not yet published, and Part II states the field relations of the rhyolite in too little detail that one can now assemble the facts bearing on this problem. A few points may be noted to indicate the general need of including foundering among the multiple hypotheses relative to the mode of extrusion represented in the rhyolite plateau.

1. Few geologists will doubt that this lava is the effusive equivalent of a salic granite. The enormous volume of the rhyolite implies a plutonic feeder of batholithic proportions, especially if we grant that all Tertiary granite (or rhyolite) is a direct or indirect product of assimilation. The solution of enough of the pre-Cambrian terrane and of the locally thin, overlying sediments to yield, after differentiation, these thousands of cubic kilometers of rhyolite, could only take place in a very large plutonic chamber. General and independent theory suggests, therefore, that a portion of the Yellowstone Park area is underlain by a granite batholith, which, like the rhyolite, is of Pliocene age, and is one of the youngest batholiths on record.

2. The scale of the extrusion, its topography, and topographic rela-

[19] C. T. Clough, H. B. Maufe, and E. B. Bailey, Quart. Journ. Geol. Soc., **65**, 670 (1909).

[20] J. P. Iddings, Monograph 32, Part 2, U. S. Geol. Survey, 1899, pp. 366 and 375.

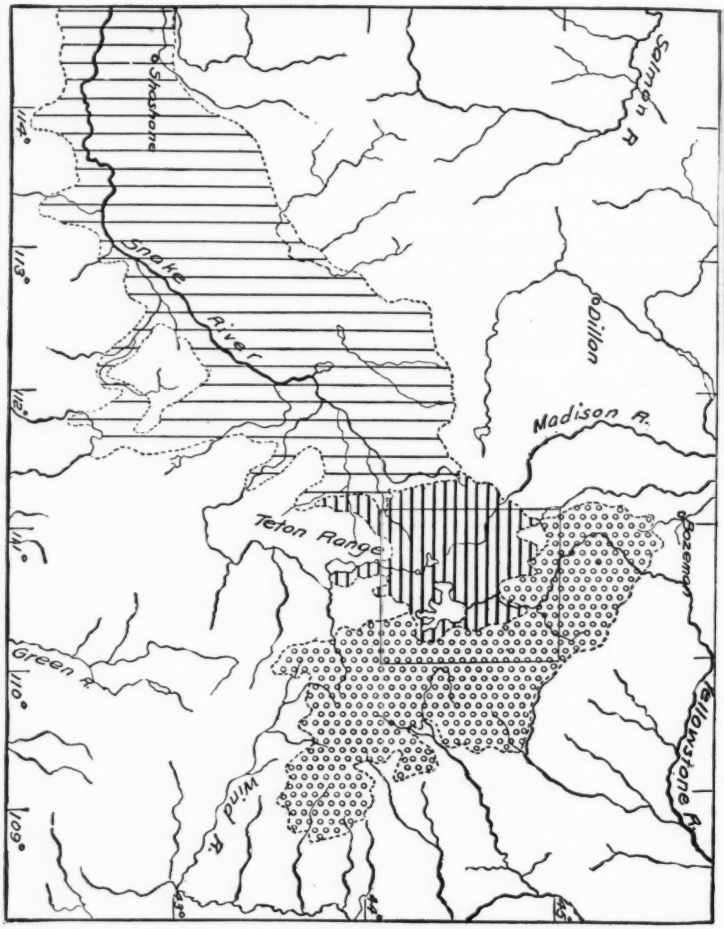

FIGURE 3. Sketch map of region embracing the Yellowstone Park (shown by rectangle on the 110th meridian); after Iddings. Small circles represent andesitic pyroclastics and flows of Eocene and Miocene age (central eruptions). Horizontal lines (map in usual orientation) represent Pliocene rhyolite of the Park (eruption chiefly by foundering). Vertical lines represent the Pliocene Snake River basalt (fissure eruption).

tions, and the relative insignificance of pyroclastic phases, are all opposed to the view that the rhyolite issued from one or more vents of the ordinary central-eruption kind. The unprecedented thickness of the lava in a single, extended mass — more than 600 meters thick for hundreds, if not thousands, of square kilometers together — is quite unparalleled in masses known to have been emitted during true fissure eruption. Moreover, Iddings points out that rhyolite dikes (feeding fissures) are almost entirely lacking in the Park.[21] The superposition of distinct rhyolite flows in the regions surrounding the main rhyolite body may be explained as due to successive outflows from the area of foundering. Thus, so far as the facts of the field declare against the central-eruption and fissure-eruption hypotheses, they appear to favor some other explanation. As yet the writer has conceived no other except that of foundering.

3. The geysers of the Park are practically confined to the area covered by the Pliocene rhyolite. In a similar way the other two great geyser-fields of the world, in Iceland and New Zealand, are located in regions where magma of liparitic (granitic) composition has been poured out at the earth's surface. The "fossil" geysers, described by Frech in the Kremnitz district of Hungary, are confined to areas of highly acid lavas.[22] Following the general argument outlined above, the liparitic lava in each of these four districts has been differentiated from one or more relatively and absolutely *large* magma chambers, i. e., in abyssal injections big enough to assimilate acid rocks in notable amount.

According to Holmes, the Yellowstone geysers were in operation long before the Pleistocene period and have been active ever since.[23] By an ingenious method Schlundt and Moore have calculated that about 20,000 years have elapsed since the Glacial period in the Park.[24] This figure agrees well with other recent estimates of post-Glacial time. Twenty thousand years is clearly much less than the total time during which the geyser activity has been sustained in the Park. Competent observers agree that the geyser waters are wholly or chiefly of meteoric origin. The thermal energy required to superheat this cold water to explosion-points during so many millenniums must be enormous. Though the spring waters are radioactive, the heat set free by radioactivity is not to be considered as of any direct importance in the

[21] Monograph 32, Part 2, U. S. Geol. Survey, 1899, p. 381.

[22] F. Frech, Aus der Natur, Vol. 1, Heft 8, 1905.

[23] W. H. Holmes, 12th Ann. Report, U. S. Geol. and Geog. Survey of the Territories, Part 2, 1883, p. 29.

[24] H. Schlundt and R. B. Moore, Bull. 395, U. S. Geol. Survey, 1909, p. 34.

problem. The thermal energy is clearly derived from magma. The small amount of water ejected in the average geyser eruption, when compared with the observed diameter of the geyser's throat below its funnel, shows that the level of superheating is, on the average, not more than a few hundred meters below the surface. The heat can hardly be regarded as that residual from a Pliocene lava-flow even 600 meters thick. The specific heat of water is from three to five times greater than that of rock-matter between the temperatures of 100°C. and 1000°C.

Allowing for radiation above and conduction below the lava flow; considering also that the rhyolite was erupted tens of thousands of years ago, that the rhyolite is comparatively permeable for the chilling rain-water, and that the visible abstraction of heat from the rhyolite by the springs is continuous and rapid, — one must doubt the hypothesis that the original heat of even such a thick flow can be responsible for the present activity of the geysers. The hypothesis suffers, too, from the difficulty that it does not explain the high temperatures of the Mammoth Springs. These emerge from a Mesozoic terrane which lost its rhyolite cover (a sheet formed by lateral outflow from the main area of extrusion) in pre-Glacial times. The same point may be urged in the case of other hot springs, such as those in the bottom of the Grand Canyon of the Yellowstone. At each of these localities the heat is passing upwards through the relatively thin roof, composed of the country-rock of the batholith.

It would, therefore, seem just to refer the geyser temperatures to one or more great subterranean masses (batholiths) extending, nearly or quite continuously, 120 kilometers from north to south and 30 to 50 kilometers from east to west. Heat will pass upward from such a batholith either by simple conduction through the roof-rock or by gaseous transfer. The analyses of the spring-waters suggest that some magmatic gas has been added to the ascending meteoric water, which may have attained its high temperature to a certain extent from the hot gas.[25] But this cause seems quantitatively insufficient to keep the geysers working at their observed speed, and simple conduction through the rock is more likely to be the essential cause.

In whichever way the heat is applied to the water, it seems clear that the actual batholith must be at or near the surface in each geyser area. The shallowness of the zone of superheating shows a very steep

[25] The peculiarly intense alteration of the rhyolite is, in part, explicable on the assumption that the magmatic gases (specially abundant in the upper part of every batholith) have slowly passed out through the rhyolite shell after that shell had solidified.

thermal gradient. That fact is inconsistent with the assumption of a thick roof over the granite batholith, and it must be remembered that the batholith has been cooling for a length of time sufficient to permit of the excavation of 600-meter canyons in massive rhyolite.

A brief study of the geysers thus lends much probability to these conclusions: first, that over thousands of square kilometers, the batholithic roof was extremely thin when the rhyolite plateau was formed; and secondly, that this thin roof was, in places, swallowed up. Briefly put, the rhyolite of the plateau is locally bottomless, in the sense that it passes downward into a typical granite batholith. The formation of the rhyolite plateau means a kind of vulcanism which evidently needs to be distinguished from fissure eruption and from ordinary crater eruption.

Central Eruptions.

The larger part of volcanic literature deals with the activities at cone and crater. Extensive and intensive as these studies have been, the number of memoirs treating of *all* the essential problems of central eruptions is very small. Yet every general theory of volcanic action must undergo the test of such a thorough questionnaire. This applies to the hypothesis that all vulcanism is a result of the abyssal injection of primary basalt. The following argument will be clearer if a preliminary list of the specific problems relating to central eruptions be reviewed. The list includes: —

1. The localization and opening of the vent.
2. The persistence of a principal vent for many thousands of years.
3. The intermittent character of the eruptivity, including (*a*) the alternation of active and dormant phases, and (*b*) the pulsatory or geyser-like quality of eruption during the active stage.
4. The origin of the heat which, by radiation in active craters, is lost in stupendous quantities.
5. The normal evolution of a vent as illustrated in (*a*) explosiveness, and (*b*) the nature of the lava emitted.
6. The mechanism of lava outflow at central vents.

These tests of our hypothesis will be briefly considered, nearly in the order given.

Opening and Localization of the Vent.

Enlarged fissures. — The events of 1783 at the famous Laki fissure of Iceland illustrate the close relation between some central eruptions and the pronounced fracturing of the surface rocks of the earth. For much or all of its length the master crack was doubtless connected with a typical, narrow, abyssal injection. Many hills of the cone-and-crater type

were built along the fissure, which emitted floods of basalt on the greatest scale recorded by man. Escape of lava from the abyssal injection was evidently much easier at some points along the visible fissure than at others. The case is analogous to the formation of the "Dewey craters" (cinder-cones) on the Mauna Loa lateral fissure opened in 1899, and of scores of similar accumulations on the flanks of Mauna Loa, Etna, etc. Dutton[26] gives this explanation for some of the necks occurring in the well known Mount Taylor district of New Mexico. In all such instances certain *points* in the fissure-lines are favored in the eruptivity, while the remainder of each fissure was either never opened clear to the surface, or else was rapidly sealed up by congealing lava.

The continuance of eruption at any point depends on victory in the *struggle with cold.* That victory in its turn depends in part on a sufficient width of vent to permit of a column of lava which is not chilled too greatly by conduction into the wall-rock. Since erupting fissures are never more than a few meters in width at the surface, it seems necessary to postulate a widening of each fissure where it carries cone and crater of prolonged activity. The widening may be conceived to depend on four different factors: solution and mechanical removal of wall-rock by emanating lavas; melting and explosive abrasion of the wall-rock by magmatic gas emitted *through* the lava column. It is not important here to decide on the relative efficiency of these processes in merely enlarging the original fissure to full vent size. Their relative efficiency becomes of fundamental significance in the problem of the persistence of eruptivity at a central vent. In the following discussion of this topic it is concluded that the vent is kept hot, and therefore active, because of the emanation of free juvenile gas rising from great depth — a process which may be styled "gas-fluxing." Since a great enlargement of an original fissure, below the bottom of any possible explosion funnel, demands much time, it would follow that most of the enlargement is due to gas-fluxing. Gaseous explosion and erosion of the walls by emanating lava might be more effective in the widening of smaller and more short-lived vents.

It is an easy step from the observed case where central eruptions are developed on fissures of lava-flooding, to the case of the formation of central vents on surface fissures from which no true fissure-eruption has ever taken place. Such a crack may be too narrow to permit the extrusion of gas-free lava, which, through quick chilling, seals the fissure, and yet the crack may be wide enough to allow passage of the

[26] Sixth Annual Report of the United States Geological Survey, 1885, p. 172.

juvenile gases from an underlying abyssal injection. Entering the crack under pressure and therefore at high temperature, these gases must tend to enlarge it by slow fusion of the wall-rock. The process may or may not be supplemented by the opening of an explosion funnel at the surface. As the vent is enlarged by gas-fluxing the magma rises within it, and, kept fluid by the emanating gas, permits of further upward blowpiping.

This mechanism implies that the original surface fissure may not be discernible by the geologist. It may correspond to no vertical or horizontal displacement, and at the surface itself be no wider than an ordinary master joint or fault fracture. Enlarging slowly downward, such a fissure might be charged with accumulating gases so far as ultimately to cause an explosion. Since the gases must tend to accumulate about one or more points along the fissure, the explosion form will be that of a vertical tube surmounted by a funnel. The resulting vent is a *diatreme*, the formation of which was so successfully imitated by Daubrée. This type of diatremes is, then, located on a surface fissure, which may or may not be continuous with the abyssal fissure of the primary injection. These considerations show the difficulty of disproving the existence of through-going crustal fissures beneath central vents.

Diatremes. — Daubrée's experiments suggest, however, that some volcanic diatremes may be formed in homogeneous, unfissured rock, and a second type, a pure explosion form, should be recognized in a full classification of vents.

A diatreme of either kind may be enlarged by the continued passage of the blowpiping gases, by the mechanical erosion of the walls by outflowing lava, or by the piecemeal stoping of the walls by the lava column.

Plutonic Cupolas. — Lastly, a complete genetic scheme should recognize a process of vent-opening which is neither explosion, nor the enlargement of through-going fissures. Most of the greater abyssal injections are strictly intrusive and do not occasion the outflow of magma at the earth's surface. Those of batholithic size show, in the field, clear evidence of having actually worked their way up the last few hundred meters or last few kilometers, before the respective magmas have solidified. The process is one of absorption of the roof-rock, and is clearly distinct from that of mere injection, either abyssal or satellitic. Both stoping and marginal assimilation are most rapid at the hottest parts of the contact between magma and country-rock. At the roof, the juvenile gases tend to accumulate in any cupola-like irregularities in the roof. These gases rise from the interior of the magma, perhaps from great depth. Because of the pressure reigning even at the roof

of the plutonic body, the gases must have high temperature, which increases as the gas-tension increases. The total mass of the gas accumulated at a cupola at any one time may be small, but it may serve to determine a more rapid incorporation of the roof-rock at the cupola than in the area of roof surrounding the cupola. It is obvious also that some roof-rocks are more easily absorbed by a given magma than are other rocks.

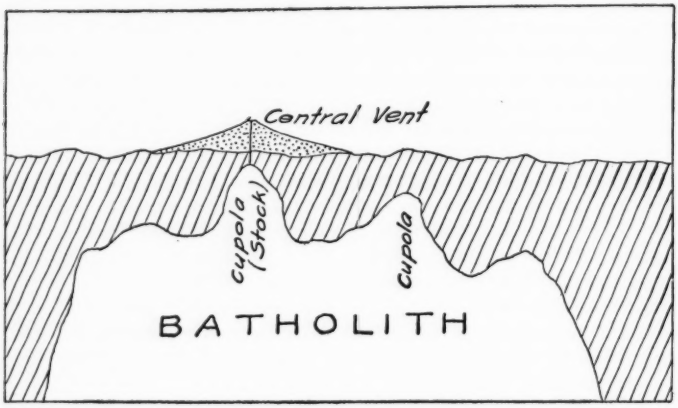

FIGURE 4. Ideal section showing formation of volcanic vent through the differential rise of assimilating magma.

The rise of batholithic magma is, therefore, differential. Partly because of gas control its attack on the roof is most efficient at *points*, rather than along lines or in large areas. (Figure 4.) This deduction seems well matched by the field fact that round intrusive bosses or small stocks are characteristic cupola forms on large batholiths. Some of these bosses have been proved to have very steep contact-surfaces and, in shape, as in their cross-cutting relations, closely simulate volcanic necks. It is evident that every such cupola increases as well as localizes the danger of true volcanic action. Blowpiping fusion or pure explosion may destroy the relatively thin roof above the cupola. The resulting vent is, then, of composite origin. Its upper part is like the two simple types of central vents already described. Its lower part is neither diatreme nor blowpiped hole, but represents the work of all the agencies of magmatic assimilation in depth. This composite type of

vent illustrates the close connection between volcanic and plutonic geology.

The original location of each first-rank vent is thus explained by the roof-topography of the underlying magma chamber. Some one of the cupola-like offshoots of the fluid magma, where it penetrates the solid rock above, must become a place for the accumulation of the rising gases. A vent once formed at the top of the cupola, it must tend to persist as a vent throughout the period of magmatic fluidity. Other vents from the same chamber may be opened, but must have shorter lives, because of the drawing away of the juvenile gases toward the more favored vent. (See Figure 7.)

Continuance of Activity at Central Vents: Analysis of Conditions at Kilauea.

Left to itself, the lava column of a vent must soon freeze and activity must cease. Long-continued activity is conditional on victory in the struggle with cold. How is the victory attained? How is the heat of the underlying magma chamber transferred to the narrow vent? Hawaiian vents supply data on this fundamental question. Though Kilauea may be the vent of a satellitic injection (see p. 109), the mechanism is doubtless the same as for a vent over a main abyssal injection.

Rate of Heat-loss through Conduction into the Walls. — It is possible to obtain a rough idea of the enormous rate at which heat is given out, by conduction and radiation, at Kilauea. (Plate I.) Actual calculation will show that radiation is much more responsible for the loss of heat than is conduction into the wall-rocks of the vent. To make this point clear it will be assumed that the cross-section of the conduit is throughout as large as the area of the lava lake, though very probably the lake represents a strongly flaring part of the lava column. (See Figure 6.) The conditions of the lake in 1909, when it was studied by the writer, are assumed. The area of the lake (and therewith the cross-section of the lava column) is considered as circular, with radius of 100 meters. This is more than the superficial extent of the lake in 1909 but less than its average extent since 1820. The cylindrical pipe with the uniform cross-section is assumed to extend to a depth of two kilometers, where it opens out into the great feeding chamber.

Let the temperature of the magma be assumed as 1200° C.; and let the average original temperature of the rocks now forming the conduit walls be assumed as 40°C. Two hundred and fifty years after the conduit was first opened and henceforth occupied by lava at the uniform temperature of 1200°C., the rate of flow of heat through the walls would be nearly uniform; and 12 meters from the contact of

the molten lava the temperature of the wall-rock would be about 1115° C.[27] This estimate is based on the assumption that the diffusivity for heat in rock at high temperature has the value given by Kelvin. That value is certainly too high, but the temperature stated for a point 12 meters from the contact would in any case be reached after some centuries following the establishment of the lava column. An idea of the heat loss by conduction may now be obtained. The equation for heat flow is :

$$Q = k \cdot A \cdot \frac{T - T_1}{x} \cdot t,$$

where k is the coefficient of conductivity, A the area of the surface traversed, x the thickness of the plate traversed, t the time, T and T_1 the steady temperatures of the two sides of the plate. In this case we may use C. G. S. units, with k 0.005 (certainly too high a value for these temperatures), t one second. x 1200, and A $2\pi r \times 200{,}000$. We have

$$Q = .005 \times 2 \times 3.14+ \times 10{,}000 \times 200{,}000 \times \frac{1200 - 1115}{1200} \times 1$$

= approximately 4,450,000 gram calories.

The result expresses the approximate amount of heat lost by conduction into the wall-rock during each second.

Rate of Heat Loss through Radiation at the Crater. — Siegl has recently supplied a datum required for estimating the heat lost by radiation from the surface of the lava lake. The general equation is

$$\log S = \log c + \epsilon \log T,$$

in which S represents the number of calories radiated per second, T is the absolute temperature stated in degrees centigrade, and c and ϵ are constants. For basalt Siegl has found that $c = (10)^{-12} \times 0.589$, and $\epsilon = 4.083$.[28] His experiments show that the equation holds for basalt up to 472° absolute. It is very probable that it may be applied, with relatively small, or at least non-significant, error, to basalt at the higher temperatures and under the conditions of radiation represented at Kilauea. Such extrapolation gives the following results :

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[27] R. A. Daly, Amer. Jour. Science, **26**, 23 (1908).

[28] K. Siegl, Sitzungsber. Akad. Wissen. Wien, Math.-Naturw. Klasse, Bd. **116**, 1203 (1907).

$t°$ C.	$T°$ abs.	S.
450	723	0.277
727	1000	1.044
1000	1273	2.800
1200	1473	5.082

In 1909 the present writer used a Féry pyrometer to determine the average temperature of the non-incandescent scum which regularly covered at least two thirds of the lava lake. The average temperature for this part was estimated to be about 450° C.; the corresponding heat loss is computed to be 0.277 cal. per square centimeter per second.

At the best points of observation in 1909, the area of the hottest lava was not large enough to cover the "black spot" of the pyrometer for a time long enough to give a reading for its full temperature. It was clear, however, from the behavior of the galvanometer needle during the brief exposures of the very hot lava in the "Old Faithful fountains," that its temperature was well above 1000° C. From the color the temperature of the hottest lava visible in the lake was estimated to be somewhat over 1200° C. The third of the lake relatively free from scum was estimated to have an average temperature of 1000° C., corresponding to a heat loss of 2.8 calories per square centimeter per second.

With radius of 100 meters the circular lake would lose in heat about 375,000,000 calories per second. The actual lake of 1909 probably lost more than 230,000,000 calories per second.

We may conclude that heat was then being lost by radiation more than fifty times faster than by conduction into the walls of the Kilauean pipe, if it be assumed as two kilometers deep. It would seem that radiation at the crater must be the dominant one of these two phases of heat loss in any strongly active volcano.

Methods of Heat Transfer. — The upward transfer of heat into a volcanic pipe might conceivably take place in five different ways: (1) by explosive removal of material from the upper part of the vent, followed by uprise of magma from the still fluid chamber; (2) by simple overflow of magma at the lip of the crater; (3) by thermal convection in the lava column; (4) by a process which may be called, for convenience, "two-phase convection"; and (5) by the passage of free juvenile gas *through* the lava column, thus bringing abyssal heat to the upper part of the vent.

The first and second processes have obviously played no essential rôles in keeping up the heat supply in Kilauea since 1823, when detailed records of its activity began.

Mere thermal convection can hardly be regarded as an essential factor in postponing the solidification of a lava column. In this matter the analogy with water heated from below should be applied only with due attention to quantitative values. The degree of superheat in the actual well-established vents is not indefinitely high; it is doubtless no more than 200° or 300° C. If convection be lively enough to keep the column molten, the maximum thermal-density differences within the vent itself should certainly be less than those corresponding to a difference of 100°. A temperature change of 100° C. means a density change in magma of less than one half of one per cent.[29] The density change in water as it passes from 4° C. to 100° C., or vice versa, is about 4.3 per cent. With a density difference about one tenth that of water in the same temperature interval, and with that difference distributed through kilometers of depth instead of through decimeters, as in the ordinary convective experiment with water, the convective potential in the lava column is evidently of a very low order. Moreover, the speed of the convection depends on the viscosity of the magma, which through chilling and through pressure is doubtless, on the average, hundreds or thousands of times more viscous than water. It follows that in resistance to be overcome, as in working potential, heat convection must be incomparably less rapid in a volcanic conduit than in artificially heated water.

For example, let us suppose that at the depth of two kilometers the conduit passes into the feeding magma chamber; that there the temperature is 1300° C., while the temperature at the surface is 1200° C.; that the average kinetic viscosity of the conduit lava is as low as that of a liquid 100 times more viscous than water; that the thermal convection in the conduit is to be compared in rapidity with that obtaining in water heated from 4° to 100° in a wide tube one meter high. The maximum convective gradient for the water system may be expressed as

$$\frac{4.3 \text{ (per cent expansion)}}{1 \text{ (meter, thickness)}} = 4.3$$

The gradient in the lava column is approximately

$$\frac{0.5 \text{ (per cent expansion)}}{2000 \text{ (meters)}} = .00025.$$

The maximum speed of convection in the water of the imagined experiment is, then, $\left(\frac{4.3}{.00025} \times 100 =\right)$ 1,720,000 or more times greater than that of the lava in the conduit.

[29] According to Barus, as quoted in Amer. Jour. Science, **26**, 26 (1908).

It seems certain that such slow transfer of magma could not keep the temperature of surface lava of the lake at anything like the observed point. On the average, every square centimeter of the lake's surface in 1909 radiated about one calory per second or 86 400 cals.

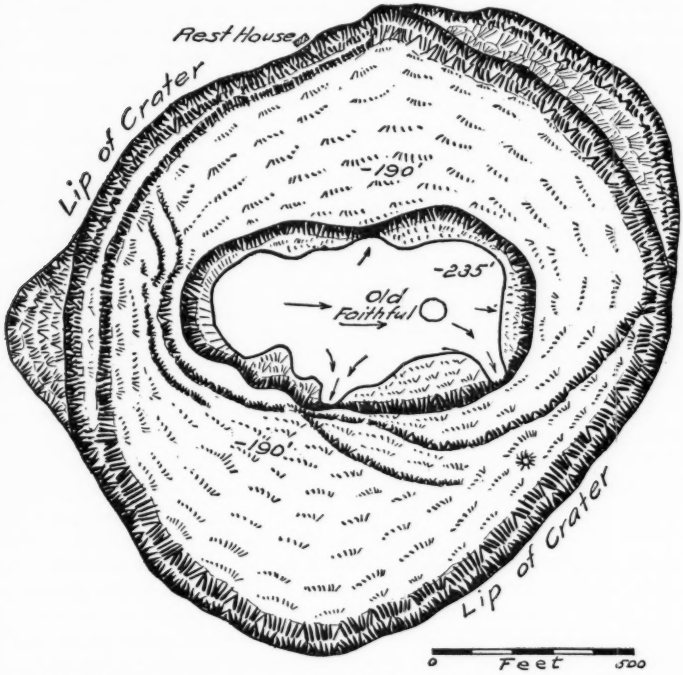


FIGURE 5. Sketch map (after J. M. Lydgate) of Halemaumau in July, 1909. Arrows indicate the general trend of currents in the lava lake during that month. The positions of "Old Faithful" and of the more important caves eroded by the liquid lava in the "Black Ledge" are shown. Figures show depths below the "Rest House."

per day. Taking .35 as the mean specific heat of basalt (1200°–1300°), this implies a daily heat loss corresponding to a temperature fall of 100° C. in a vertical column of lava more than 2400 meters deep, and one square centimeter in area at its upper surface. Evidently, other and much more effective agencies must be at work to keep Kilauea active, year in and year out.

Two-phase Convection. — However, there is a different and very powerful kind of convection constantly illustrated in Halemaumau when that lake is in full activity. (Figure 5.) The persistent streaming of the lava into the caves, characteristically developed at the shore cliffs of the lake, is evidently due to surface gradients. In general, the "scum" stands higher in the central part of the lake than it does in the caves and in the channels leading to the caves. The "scum" or thin crust of the lake prevents or retards the escape of the magmatic gases, which accumulate beneath it and form a kind of froth, or emulsion of lava and gas, of relatively low density. The tendency is, thus, to raise the crust in one or more areas. In each cave, because of reflection from its roof, and perhaps also because of special heating through actual combustion of sulphur, hydrogen, and other gases, the crust is rapidly and completely fused. The escape of the gases is there facilitated and the surface of the lava is correspondingly lowered. The surface slopes are, therefore, steepest in the channels leading to the caves, and streaming at the rate of two to five kilometers an hour may be observed in the channels. Elsewhere the surface slopes are lower and streaming is less rapid. The caves are not outletting tunnels, as so often stated, but each is closed at a distance of a few meters from its entrance. The lava which has streamed into the cave must return to the main part of the lake. Only one way of return is possible, that by a backward sub-surface current. Having lost its dilating gas and grown rapidly denser, the heavy lava sinks and flows toward the center of the lake. Similarly, the ever-changing surface slopes in other parts of the lake compel vertical currents and vortices of the most complex design. (Figure 6.) This type of magmatic movement may be called "two-phase convection."[30] It depends on the presence of a liquid "phase" and a gas "phase" in the lava.

If vesiculation of the liquid magma is possible in great depth, two-phase convection may cause a relatively speedy transfer of hot magma to the surface. How effective this process can be is worthy of somewhat detailed statement. The imposing change in magmatic density, which is effected by very slight increase in vesiculation, will first be indicated. The speed at which individual bubbles rise will then be estimated, and, finally, a rough quantitative idea of the convection enforced by the development of gas bubbles in depth will be obtained.

The specimens of Hāwaiian pahoehoe lava collected by the writer

[30] The term "two-phase," so convenient in describing this type of convection, was suggested to the writer by Dr. W. C. Bray, of the Massachusetts Institute of Technology.

contain, on the average, at least 200 vesicles per cubic centimeter of the lava. The vesicles of the surface layers are roughly spherical and average no more than 2 mm. in diameter, though, of course, the range of diameters is very great. For convenience, let a spherical mass of hydrogen, having the radius of 1 mm. at one atmosphere of pressure and at 1200° C., be called the "standard bubble" for basalt. Extrapolating on Amagat's pressure-volume curves for hydrogen at 1200°C.,

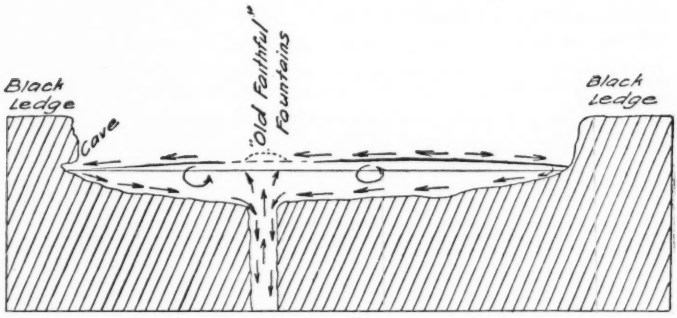


FIGURE 6. Diagrammatic section of Halemaumau, illustrating two-phase convection, erosion of caves, and vortical action. The lava "scum" is represented by the heavy black line at the lake surface. Length of section about 300 meters. Vertical scale specially exaggerated in drawing the "scum" line.

the volumes and radii for the standard bubble at high pressures may be calculated within a margin of error which is probably very small. Examples are shown in the following table :

Approximate depths in magmatic column (meters).	Pressure in atmospheres.	Volume (cm.³).	Radius (cm.).
730	200	0.000115	0.030
3650	1000	.000025	.018
7300	2000	.000014	.015

Gas-free basalt at 1200°C. and one atmosphere has a specific gravity of about 2.75. On account of the slight compressibility of rock-matter, that value may be assumed as typical for gas-free basaltic magma at pressures up to several thousand atmospheres. If such magma become charged with 200 standard bubbles per cubic centimeter, at 200, 1000, and 2000 atmospheres, the specific gravity falls to the following approximate values (Col. 1) :

Pressure.	Specific Gravity.	
	1.	2.
200	2.688	2.7495
1000	2.736	2.74975
2000	2.742	2.74997

A single standard bubble replacing the liquid in each cubic centimeter of gas-free basalt would lower the specific gravity to the amounts shown, again approximately, in Col. 2.

This last table illustrates possible ranges of buoyancies induced by vesiculation at the three depths chosen. The actual buoyancy attained may often be much higher. It will be seen that the buoyancy produced by only a small extra vesiculation of a local mass of magma must occasion a rapid uprise of that mass.

The bubbles themselves, as independent bodies, must rise with comparative slowness. The experiments of H. S. Allen have shown that small spherical bubbles, rising in a liquid, attain their terminal velocity according to the formula previously deduced by Stokes for the rise of light solid spheres of very small radius.[31]

Let r represent the radius of a bubble; d', its density; d, the density of the surrounding magma; v, the coefficient of viscosity of the magma; g, the acceleration of gravity; and x, the terminal velocity of the rising bubble, that is, the velocity when the motion is steady. The Stokes formula applies if the product dxr is small compared with v. This is clearly true for the standard bubble in liquid basalt with the viscosities appropriate to pressures of 200 to 2000 atmospheres. We have, then,

$$x = \tfrac{2}{9} gr^2 \left(\frac{d - d'}{v} \right).$$

Computing the values of x when the magmatic viscosity is assumed to be constant and only 100 times that of water at 15° C. (0.0115) or 1.15 in C. G. S. units, we have, at the three illustrative pressures:

Depth (meters).	Pressure (ats.).	Terminal Velocity (x).	
		Cm. per Second.	Meters per Hour.
730	200	0.47	16.9
3650	1000	.17	6.1
7300	2000	.12	4.2

[31] H. S. Allen, Phil. Mag., **50**, 323 and 519 (1900). G. G. Stokes, Cambridge Phil. Trans., **9** (2), 8 (1850).

Since experiment shows that the viscosity of a liquid rises rapidly with pressure, it is instructive to assume higher values of v for the greater pressures. If v be taken again arbitrarily as 500 and 10,000 times that of water for magma under the pressures of 1000 atmospheres and 2000 atmospheres, respectively, we have for x these values :

Pressure (ats.).	Viscosity.	Terminal Velocity (x). Cm. per Second.	Meters per Hour.
200	1.15	0.47	16.9
1000	5.75	.034	1.2
2000	115.00	.0012	.04

In all cases smaller bubbles would rise more slowly, x varying directly as the square of the radius.

Two important conclusions may be drawn from these computations. Gas bubbles of the "standard" mass or of smaller mass must rise from the deeper levels of an abyssal injection with extreme slowness. In view of the high magmatic viscosity and great pressure in depth, it is conceivable that it may take thousands of years for a "standard" bubble to rise from a depth of, say, ten kilometers to the earth's surface. This suggests one reason why gaseous emanation is so prolonged at central vents.

Secondly, from the slowness with which bubbles rise, it is clear that a swarm of bubbles, which for any reason have been aggregated locally in special abundance, would be dispersed into the surrounding, less vesiculated magma with great slowness. The local mass of magma thus specially vesiculated would be less dense than the average magma and, as a unit, would rise toward the crater. It now remains to indicate that a very moderate amount of extra vesiculation must cause such a two-phase mass to rise with comparatively great velocity.

Of course, this case has not been investigated experimentally; an indirect method must be used in its discussion and the result can at present hardly be other than qualitative.

Once again to make the mental picture clearer, it is well to assume certain conditions arbitrarily. As an example, let the swarm-filled mass be spherical; let the reigning pressures and magmatic viscosity be as in the foregoing cases; let the surrounding magma have a density of 2.75; and let the extra vesiculation be to the extent of 50 "standard" bubbles per cubic centimeter on the average. The corresponding densities of the sphere are shown in the second column of the following table :

Pressure (ats.).	Sp. Gr.	$d-d'$.	v (assumed).	R (cm.).
200	2.734	0.016	1.15	0.52
1000	2.746	.004	5.75	2.40
2000	2.748	.002	115.00	22.25

For solid spheres rising in the magma we may compute the "critical radius" (R), that is, the radius of the largest sphere which would obey the law of the Stokes formula. The values for R, as stated in the fifth column, have been found with the help of Allen's formula : [32]

$$R^3 = \frac{9\,v^2}{2\,gd\,(d-d')}.$$

The terminal velocities of the solid spheres having the critical radii would be, for the corresponding values of R, v, and $(d-d')$, as follows :

$d-d'$.	v.	R (cm.).	Terminal Velocity. Cm. per Sec.	Terminal Velocity. Meters per Hour.
0.016	1.15	0.52	0.82	29.5
0 004	5.75	2.40	.87	31.4
0.002	115.00	22.25	1.88	67.6

The figures show that even for small solid spheres the velocities are considerable. With increase of radius the terminal velocities would at first increase very fast, and then more slowly. However, since the resistance to the motion would, for large spheres, vary with the square of the velocity, neither the Stokes formula nor any other yet developed can declare the actual velocity for large solid spheres moving in the magma.

Nevertheless, Allen's formula for large spheres is of distinct help in guiding one to a proper appreciation of the case. It reads :

$$V^2 = \frac{1}{k} \cdot \frac{4\,\pi}{3} \cdot gr \cdot \frac{d-d'}{d},$$

where k is a constant for a given liquid-solid system.[33] It follows that the terminal velocity here varies directly as the square root of the radius and as the square root of the difference of the two densities. Referring to the table showing terminal velocities for solid spheres with critical radii, it seems clear that, in any of the three cases, spheres of

[32] H. S. Allen, Phil. Mag., **50**, 324 (1900).
[33] H. S. Allen, Phil. Mag., **50**, 532 (1900).

corresponding density and of radii of 10 or more meters would rise at the rate of at least 10 centimeters per second or 360 meters per hour.

This analogy of solid spheres seems to afford some help in our imagining the course of a specially vesiculated mass of liquid magma. The rough quantitative estimate just made for large solid spheres cannot be directly applied to this case. On account of the possibility of internal movements in the rising mass of liquid magma, its speed of uprise will not be quite the same as that of a solid mass of the same shape, size, and density. Yet the correction to be applied is probably small.

As such a mass approaches the surface, through a column of rapidly decreasing viscosity and with a constant increase of buoyancy because of expansion of the contained bubbles, the velocity must greatly increase. However much a given mass of magma might lose buoyancy through the loss of its larger, more swiftly rising bubbles, the total effect must be to generate a powerful upward current in the magmatic column.

In spite of the lack of the necessary, full experimental data, our general conclusion seems to be as follows. Experiment does show that the rise of individual gas bubbles in magma will be very slow. Neither experiment nor theory can as yet declare the actual speed of the rise of a mass of specially vesiculated magma, but the analogy of solid spheres moving under gravity in a liquid enforces the belief that the more buoyant magma will move rapidly if its volume is of the order of thousands of cubic meters. Assuming such differential vesiculation in great depth, and assuming also a mechanism by which the gas of risen magma is dissipated (as in a volcanic vent), two-phase convection must stir the magma column to great depth and with considerable rapidity. Such a process must be incomparably more rapid than that of thermal convection under volcanic conditions. The transfer of heat may readily be conceived as able to supply the radiation loss in the crater for long periods of time.

The basal assumption, that vesiculation occurs at great depth in a volcanic conduit, is necessarily difficult to test by the facts of field geology. During its solidification an intrusive body is likely to be cleansed of its bubbles, which rise, and the gas so collected at the roof is slowly dissipated into the country-rock. This may be the explanation of the lack of vesiculation in most dikes, sheets, laccoliths, and batholiths. In general, the rock of a lava neck may be similarly freed from bubbles during the relatively long period of crystallization. Nevertheless, cases are not wanting where bubbles are known to have been trapped in basalt at depths greater than 300 meters. The basalt of the West Maui neck, illustrated in Figure 10, is charged with many minute vesicles at a

depth at least 300 meters below the original top of this lava column. Ransome (in Bulletin 303 of the United States Geological Survey, 1907, p. 68) states that the bottom of a single 320-meter flow of basalt at Eldorado Canyon, Nevada, is vesicular. These and other known examples seem to strengthen the belief that bubbles may form in magma at the depth of several kilometers.

It is important to note that two-phase convection has two distinct, though related causes. Principal stress has hitherto been laid on differential vesiculation in depth, whereby a mass of magma becomes more buoyant than the enclosing magma and rises. Just as inevitably, the magma which is freed of gas at the crater, must sink and stir the column to great depth. Even if the column is not vesiculated at all, this second mode of convection is likely to be effective in the vertical transfer of the magma. As a rule, the density of a liquid is lowered by the absorption of hydrogen, nitrogen, oxygen, or other relatively light gas. This is very probably true of natural mixtures of juvenile gases when dissolved in magma. As these gases stream or diffuse from all azimuths in the feeding chamber toward the base of the narrow conduit, they are there concentrated. Thus, the magma *in* the conduit, at its lower levels, attains a density less than that of the average magma of the feeding chamber, and, a fortiori, less than that of the gas-freed magma descending from the crater level. This is another kind of density convection depending on the relative concentration of juvenile gas. For lack of experimental data, it is now impossible to estimate the efficiency of this species of convection. It may be a powerful ally of two-phase convection proper. For example, it is conceivable that the upward movement of magma is *begun* in the conduit because of the concentration of gas in solution and not in bubble phase. Then, as the magma rises to levels of smaller pressure, the gas begins to separate out in bubbles and enforces true two-phase convection of ever-increasing speed. In view of these various modes of gas-control, the vertical stirring of the magma column may, perhaps, be more safely described as, in general, a gas-concentration convection. Yet, the actually observed fact is that, at the crater, the gaseous phase does separate, in bubble form, from the liquid phase, and the writer has preferred to emphasize this empirical fact in adopting the name "two-phase convection."

Lava Fountains. — Herein the writer believes that we have an essential part of the explanation of "Old Faithful," the site of the greater periodic "fountains" of Kilauea. (Plate II. B.) That circular area, about twenty meters in 1909, has represented the true axis of the lava column for many years, and seems to have been the main source of

magmatic heat throughout the known history of Kilauea. In 1909, at average intervals of about thirty-five seconds, the surface of the lava lake in this area was domed up to maximum heights of a few meters. These fountains are not due to the rise and explosion of great gas bubbles, the collapse of which could have been readily observed. No appreciable amount of gas or vapor was given off at the moment of doming or immediately afterwards. The outbursts are best explained, in part, on the principle illustrated in the upspringing of a log of light wood freed at the bottom of a lake. Through its momentum the log may jump clear out of the lake. In part, the outbursts of "Old Faithful" are due to true explosive dilation of the gas bubbles in the "log." The latter process is doubtless the chief cause of the smaller "fountains" playing over the surface of Halemaumau, and of those which played over the surface of Dana Lake or New Lake twenty-five years ago. The draining of each of these two lakes has shown that it was saucer-shaped and very shallow over most of its area, and the writer believes this is true of Halemaumau to-day. (Compare Plate III.) The depth is generally much too small to allow of such momentum in magmatic "logs" that they might leap to the heights actually observed.

The site of "Old Faithful" is, thus, the place where the juvenile gases rise from the depths in two-phase mixture with liquid lava. With the collapse of each dome, the gas-charged magma finds its level and runs under the semi-solid or solid "scum" on the lake surface. (Figure 6.) There the gas is slowly freed and accumulates beneath the "scum" until the tension produces a true explosion, that is, one of the many smaller "fountains" so constantly appearing on the lake.

The incessant streaming in Halemaumau, the nature of the "Old Faithful fountains," and the ceaseless vortical motion in the lake, as well as the similar phenomena in the active Mokuaweoweo, are so many direct evidences of two-phase convection, which calculation shows must be rapid, provided slight variations in vesicularity occur in the depths of the lava column. Though it is not possible to prove absolutely that the Kilauean column is vesiculated in depth, it certainly is so at the surface to a remarkable degree. At many points, the lower part of the wall of Halemaumau was found, in 1909, to be covered with thin coatings of black glass which represented splashes of lava from the adjacent lake. This lava almost instantly "froze" to the wall. In every case it was extremely porous, so as to be quite spongy in appearance. The vesiculation was almost if not quite complete before the "splash" struck the wall, and it is simplest to suppose that the surface lava of the lake is a froth. There is no known reason why

vesiculation should be the rule at one atmosphere of pressure and non-existent at one hundred or one thousand atmospheres; it is all a question of the degree of saturation with gas. The two-phase convection hypothesis rests on this unproved assumption, but its merit is great, as it explains the essential facts of circulation in Halemaumau. The hypothesis also explains the periodicity of "Old Faithful." Throughout the years 1908 and 1909 its geyser-like uprush occurred, on the average, once every 35 seconds or thereabouts. This pulsatory effect is expected as a result of the mechanism of two-phase convection.

Cooling by Rising Juvenile Gas. — As a fifth hypothesis it might be conceived that the heat is kept up in the lake through the rise of bubbles of *free* juvenile gas from the magma chamber, the bubbles arriving at the surface with some excess of temperature above that required to give the lava of the lake its observed fluidity. But the feeble explosiveness of the emanating gas at Kilauea shows that any unit mass of it, arriving at the surface, is already nearly expanded to the volume appropriate to one atmosphere of pressure, and therefore that the gas is in nearly perfect thermal equilibrium with the enclosing lava at the surface. Such bubbles, as they rise and expand, must thereby tend to cool the magma.

The cooling effect is very great, as may be shown by the following calculation. In an adiabatic expansion of a perfect gas: let T' be the initial absolute temperature, and T the final absolute temperature; let p' be the initial pressure, and p the final pressure; and let $\gamma (= 1.4)$ be the ratio of the specific heat of the gas at constant pressure to its specific heat at constant volume. Then

$$\frac{T'}{T} = \left(\frac{p'}{p}\right)^{\gamma-1}.$$

At about 37 meters below the lake surface the pressure is 10 atmospheres. If the bubble, after expanding adiabatically, is to arrive at the surface at a temperature of 1200°C., it must have at the depth of 37 meters a temperature of about 3700°C. (assuming no dissociation of the gas). Evidently the free-moving gases have a cooling effect on the upper part of the lava column. That this effect is actually small is, of course, due to the small mass of gas emitted in a unit of time and to the fact that γ is much less than 1.4 for the actual (not "perfect") gases while rising through the deeper levels. Moreover, it has been noted that the rise of a bubble must be exceedingly slow if its mass is anything like that in the average vesicle of frozen lava. So slow is the transfer that the rapid heat wastage at Halemaumau cannot possibly be compensated by any residual superheat in the emanating gas.

On the other hand, the thermal conditions are different in craters floored with highly viscous lava. There the emanating gases commonly issue at pressures of more than one atmosphere, and they are thus kept hot and endowed with some fluxing power. The small blowholes in Kilauea, as in most other basaltic districts, have long been kept open through this action. It is quite possible that such hot-blasting is operative on a greater scale in larger openings like the crater of Stromboli. Yet even at Stromboli that cannot be the chief method of heat transfer from the depths, and again no other method than that of two-phase convection seems competent to keep the lower and greater part of the lava column fluid. At Kilauea, at the wonderful Mokuaweoweo (the vent of a main abyssal injection), at Matavanu in Savaii, we seem compelled to exclude all other agencies for heat transfer except this type of convection. The same explanation seems to apply also to Vesuvius and Stromboli, for their craters in times of strong activity have been observed at close quarters and, like Halemaumau, they show lava "fountains" and other features of this convection.

The Volcanic Furnace. — So far, no assumption has been made that the heat transferred to the top of the volcanic conduit is other than primary in origin, that is, heat due to the initial temperature of the parent abyssal injection. Such is the orthodox view of volcanic heat. The rough estimate made in the discussion of thermal convection suggests the difficulty of understanding how the mere primary heat suffices to explain the long life of many volcanoes.

It may well be questioned, however, that all the heat at a volcanic vent is primary.[34] That due to the radioactivity of magma during the fluid stage of an abyssal injection is too small in amount to affect the rate of heat loss to any sensible degree. More promising is the idea that heat-producing chemical reactions in the conduit may have powerful effect. Since the day when Sir Humphry Davy renounced his own explanation of magmatic heat as due to the oxidation of alkaline metals contacting with water, most volcanic theories have regarded magma as inert so far as exothermic reactions are concerned. On the other hand, recent studies of gaseous emanations from active volcanoes and from artificially heated rocks and meteorites clearly suggest the possibility of such reactions.

Analysis of any perfectly fresh igneous rock shows the presence of water to a considerable percentage by weight. This is true of intrusive gabbros and diabase as well as of basaltic lavas. Most of

[34] Cf. G. Tschermak, Sitzungsber. Akad. Wiss. Wien, **75**, 162 (1877), where a brief statement is given, showing a clear anticipation of this hypothesis.

the non-hygroscopic water determined in the analysis of quite unaltered gabbro or basalt may be as much a primary constituent as the silica or the alumina. We must believe that hydrogen and oxygen, in the proportion characteristic of water, are present in primary basaltic magma. It does not follow that, under volcanic conditions, these elements will issue from the vent in combination as water. In his able monograph on "The Gases in Rocks," R. T. Chamberlin indicates the general reaction to be expected in the Kilauean or other basaltic magma chamber. He writes:

"The effect of pressure on chemical equilibrium is to favor the formation of that system which occupies the smaller volume, but if there is no change in volume, in passing from one system to the other, the increase of pressure presumably has no influence on equilibrium. In the reaction

$$3FeO + H_2O \leftrightarrows Fe_3O_4 + H_2$$

considered as a thermochemical equation, the number of gaseous molecules, and hence the volume of gas, always remains the same, so that it is not likely that this action will be influenced by change of pressure. A rise of temperature favors the formation of that system which absorbs heat when it is formed. A comparison of the amount of heat liberated by oxidizing three molecules of FeO to Fe_3O_4 and one molecule of H_2 to H_2O shows that, in the former case, 73,700 calories are evolved, and in the latter, 58,300; that is, $3FeO + H_2O \rightarrow Fe_3O_4 + H_2 + 15{,}400$ calories. As heat is evolved in this process, a rise of temperature would accelerate the reaction in this direction less than in the reverse. In other words, the higher the temperature, the more would the formation of ferrous oxide and water be favored as compared with the conditions at lower temperatures.

"Because of this, there is much reason to suppose that, at the depths where lavas originate, hydrogen and oxygen exist combined as water, since up to temperatures of 2000° C., the dissociation of water takes place only to a limited extent. If a state of equilibrium between hydrogen, water, and the iron compounds were established in the heated interior where a magma originated, as soon as it commenced its way upward and began to lose heat the condition of equilibrium would be destroyed. With the falling temperature the tendency to reestablish equilibrium would favor the formation of that system which was produced with the liberation of heat, *i. e.*, magnetic oxide and free hydrogen. In ascending lavas which are losing heat, the tendency, therefore, is to produce hydrogen and magnetite, or ferroso-ferric compounds. This is doubtless an important source for the hydrogen which

is so copiously exhaled during a volcanic eruption. At the same time this process accounts for the widespread occurrence of magnetite in igneous rocks." [35]

The abundant animal life of Cambrian and later time implies that the earth's atmosphere has long had a very low content of carbon dioxide. The amount of this oxide which has been locked up in the carbonate rocks since the beginning of the Cambrian period is so enormous

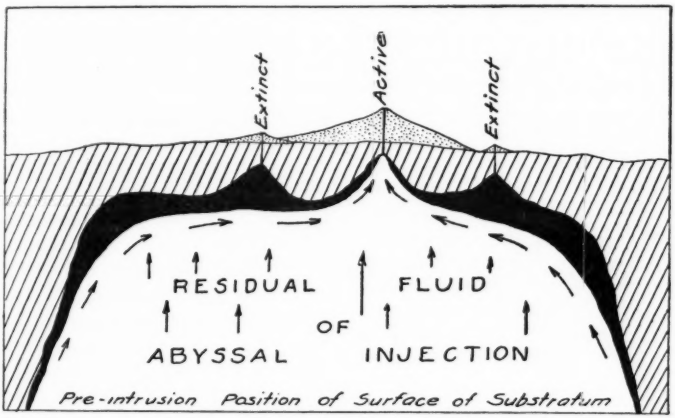


FIGURE 7. Ideal longitudinal section of an abyssal injection, showing the relation of vulcanism to the secular rise (arrows) of juvenile gas. The middle vent is active because it originates at the highest point (cupola) in the injected body. The other vents are extinct because of this advantage of the middle vent. Solid black represents the already crystallized material of the injection. Cross-lined area is the country-rock. Length of section about 100 kilometers.

that most of it, or all of it, must be considered as of juvenile origin. Yet more clearly than in the case of water, carbon dioxide must be regarded as a primary constituent of earth magma. Under the same conditions as those described by Chamberlin, ferrous iron is oxidized to magnetite by carbon dioxide, yielding carbon monoxide and 6000 calories per gram molecule.

The list of the juvenile gases and vapors also includes nitrogen, chlorine, sulphur, and hydrocarbons. These and other volatile sub-

[35] R. T. Chamberlin, The Gases in Rocks, Publication No. 106, Carnegie Institution of Washington, 1908, p. 66.

stances, including hydrogen and carbon monoxide, stream from all azimuths in the magma chamber to the lower end of the conduit. The pipe has always a very much smaller cross-section than the feeding chamber, implying some concentration of the volatile matter. (Figures 7 and 8.) At conduit temperatures this ever-varying mixture of gases must, according to practically infinite probability, be in unstable chemical equililibrium; under the conditions new equilibria are attained with the evolution of heat.

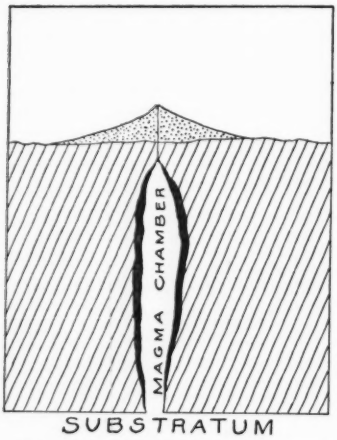


FIGURE 8. Ideal cross-section through middle cone shown in Figure 7, to same scale.

The relative proportions of each gas must, in general, be different from that in the primary magma before it was injected. Concentration of the gases means, according to the law of mass-action, the development of new compounds. As the pressure is less in the conduit than in the underlying chamber, the viscosity of the magma is less, the gas bubbles are larger, and the speed of possible reactions is thereby increased.

Of course, the actual amount of heat evolved during the chemical rearrangements in the conduit cannot be estimated, but a glance at the following tables (showing some examples) must assure one that the heat product from the complex system may be of a high order.[36]

HEATS OF FORMATION.

	Calories per Gram-molecule.		Calories per Gram-molecule.		Calories per Gram-molecule.
[HCl]	+22,000	[SO_2]	+71,080	[$CaCl_2$]	+190,300
[H_2O]	58,300	[CO_2]	96,960	[K_2Cl_2]	211,220
[H_2S]	5,400	[SO_3]	103,240	[Na_2Cl_2]	195,380
[H_3N]	11,890	[P_2O_5]	369,900	[$FeCl_2$]	82,050
[H_4C]	21,750	[FeS]	24,000		
[CO]	29,000	[CaF_2]	238,800		

[36] The values for the heats of formation and reaction are taken from the works of Thomsen, Muir and Wilson, Nernst, and others. In some cases more recent experiments give slightly different values.

HEATS OF REACTION.

$CH_4 + 2O_2 = CO_2 + 2H_2O + 195{,}200$ cals.
$CO_2 + H_2 = CO + H_2O + 9{,}980$ cals.
$3FeO + H_2O = Fe_3O_4 + H_2 + 15{,}400$ cals.
$3FeO + CO_2 = Fe_3O_4 + CO + 6{,}000$ cals.
$NH_3 + HCl = NH_4Cl + 42{,}500$ cals.[37]
$CO + O = CO_2 + 68{,}040$ cals.

In addition, there is the possibility that a large supply of energy was potentialized at the high temperatures of the primitive earth and that this energy becomes converted into magmatic heat under the conditions of a volcanic vent. Becker has suggested this in the case of uranium.[38] Arrhenius has proposed the hypothesis that the heat of the sun is supplied principally through the break-up of endothermic compounds.[39] Warren has shown that, at high pressure and temperature, steam is partially converted into the strongly endothermic ozone and hydrogen peroxide.[40] Lines indicating cyanogen are found in the spectra of some stars and comets, and Arrhenius attributes the nitrogen of the air largely to the dissociation of volcanic cyanogen. In the formation of a gram-molecule of this gas, 65,700 calories are potentialized. The dissociation of chlorine involves the absorption of 113,000 calories.[41] Dissociation of other gaseous elements means heat absorption of the same order of magnitude. When ferric oxide and iron sulphide react to form ferrous oxide and sulphur dioxide, 80,640 calories are absorbed. When carbon and carbon dioxide react to produce carbon monoxide, 38,800 calories are absorbed. When steam and C react to form carbon monoxide and free hydrogen, 28,900 calories are absorbed.

In addition to the heat evolved by the dissociation of endothermic compounds, another source of great energy is to be found in the combination of the freed, "nascent" elements with other constituents of

[37] Though ammonium chloride may not be able to form within the magma column of a volcanic conduit, it does form at the surface, where the loss of heat chiefly occurs. Similarly, ammonia may form from its elements in the relatively cool crust of the lava lake in a crater, also producing heat at the zone of radiation.

[38] G. F. Becker, Bull. Geol. Soc. America, **19**, 146 (1908). The final yield of radium is about 2,000 millions of calories per gram, or nearly 250,000 times the thermal value of a gram of carbon burnt in oxygen.

[39] S. Arrhenius, Worlds in the Making, New York, 91 (1908).

[40] H. N. Warren, Chem. News, **77**, 192 (1898). When one gram of oxygen is converted into one gram of ozone, 750 calories are absorbed.

[41] M. Pier, Zeit. für phys. Chemie, **62**, 385 (1908). Ekholm has suggested that the formation of "elements" may partly explain solar energy.

the magma. The powerful thermal effect of interaction between hydrogen or oxygen and the carbon or nitrogen atoms of cyanogen hardly needs quantitative statement to show its value.

In this connection it may be noted that the total melting heat of ordinary rock-matter (measured from 0°C.) is only 400 to 450 cals. per gram, and that the latent heat is only about 90 cals. per gram.

Such examples emphasize the value of the conception that abyssal injection, entailing a sharp change of pressure and a slower change of temperature in primary magma, may set free a vast amount of energy which is available for conserving the melting temperature in a lava conduit. Very great superheat is, however, prevented by two-phase convection, which tends to keep the volcanic furnace and the surface lava at nearly the same temperature.

The whole system, as imagined, is somewhat analogous to a modern hot-water plant with an almost perfectly lagged vertical pipe running up from the furnace. Or, again, the generation of heat in the conduit is analogous to that in the gas-mixture of a blowpipe. In the first case (two-phase convention) the rising gas is a passive agent in the upward transfer of heat; in the second case (chemical changes) the gas is a positive heater. For a double reason juvenile gas has fluxing power in the vent.

Summary on the Heat Problem of an Active Central Vent.— A volcano of the central-eruption type, like all others, depends on antecedent abyssal injection of magma into the earth's crust, furnishing a magma chamber whence the vent may draw its supply of energy.

Three possibilities are open: (1) The primary magma may have been initially saturated with juvenile gas at the original pressure of 10,000 atmospheres or more. (2) Only the upper part of the magma may be saturated with gas because of the change of pressure resulting from the injection. (3) Or the magma may not be saturated immediately after injection, even at the pressure of one atmosphere.

In the first case, bubbles must form throughout the chamber at all levels above the original depth of the magma. In the second case, bubbles must form at all levels above the lowest one where saturation has been developed by change of pressure. In the third case, bubbles will form only after other causes than mere change of pressure have operated. At least three such causes are conceivable. (a) The upper part of the magma chamber might become supersaturated through the upward molecular diffusion of gases, whereby these are concentrated. This is a reasonable expectation on the general principles of physical chemistry, though experimental or other proofs are lacking. (b) The slow crystallization of the magma might be accom-

panied by the ejection of gas, as it is actually seen to emanate during the crystallization of artificial slags. That process might cause local supersaturation in the still liquid magma, with the formation of bubbles. (c) Chemical reactions in the magma, such as the generation of hydrogen from dissolved primary water vapor — a reaction to be expected with a slight fall of temperature — might produce gases insoluble in the magma at the pressure reigning at the place of the reaction.

Among so many possibilities, it seems legitimate to assume the generation of free gas in the main magma chamber. Irrespective of their origin, the bubbles must rise with great slowness through the magma chamber, because, first, they are of small size; and, secondly, because the viscosity of magma under great pressures must be relatively high. Even in the case of supersaturation in all parts of the new abyssal injection, the entire freeing of the bubbles may occupy many thousands of years.

As the bubbles rise, the gas tends to be concentrated in the volcanic conduit. There the laws of mass-action and of the degradation of energy seem to enforce exothermic reactions of the gaseous constituents among themselves and with the elements of the liquid magma. It is most probable that the heat so generated is very great when compared to the mass of matter participating in the reactions. The conduit is thus a furnace where the potential energy of the accumulating gases is converted into heat energy.

Other sources of heat which aid in prolonging the activity of the volcano are: (a) the conversion of the potential energy of the liquid components of the magmatic system when thrown out of chemical equilibrium by the change of pressure and subsequent lowering of temperature; (b) the liberation of latent heat in the slow crystallization at the walls of the magma chamber; and (c) some degree of initial superheat in the magma, perhaps of the order of 100° or 200° Centigrade.

Since the loss of heat at an active vent is chiefly due to radiation at the crater, the continuance of activity is controlled by the efficiency of the mechanism by which the heat of the main chamber and the heat chemically generated in the conduit are transferred to the earth's surface. Field observations at Kilauea and elsewhere, along with a priori deductions, have suggested the general dominance of two-phase convection (or, more generally, convection due to systematic, local changes in gas-concentration) in making this transfer.

Juvenile gas is thus conceived to act in a two-fold capacity — as a positive heater and as the agent enforcing convection. Its net effect

is to keep fluid the top part of the lava column during the volcano's activity. The conception as a whole may therefore be called the *gas-fluxing* hypothesis. For vents occupied by highly fluid lava this hypothesis as just stated seems to suffice. For craters floored with more viscous lava, the emanating gas issues under more or less high pressure and may function as a melting blast, making more perfect the analogy with an artificial blowpipe.

Revival of Activity at the End of a Dormant Period.

One of the leading problems in vulcanism relates to the periodicity of central eruptions. This also seems to find explanation on the gas-fluxing hypothesis. We have seen that the accumulation of gas bubbles in the conduit must be a very slow process. So long as the vent is open, the escape of the gas from the magma is specially facilitated. That is true, not because the pressure on the main part of the lava column is less than in times of dormancy, but because of the rapid freeing of gas into the open air, with the consequent rapid production of heavy, gas-freed lava which sinks and thus hastens the two-phase convection. The tendency is, therefore, sooner or later to exhaust the gas concentrated at the lower end of the conduit. With sufficient removal of the heat-producing and heat-transferring agent, the forces of cold temporarily win in the never-ceasing struggle and the lava solidifies at the surface; a plug of greater or less thickness is formed. The crater may become temporarily so dead that even solfataric action ceases and a forest may flourish within the crater, as has been the case with Vesuvius.

On account of the small horizontal dimensions of the average vent, the consolidation of such a lava plug may be completed in a few years. This new rock is characteristically tough; when cooled, it is the strongest rock in the average volcanic cone. In the text-books on dynamical geology and in special vulcanological memoirs, the removal of the plug is usually stated to be due to simple explosion of the gases accumulating below it. Yet it is obvious that in the normal cone, which is largely built of loose ash deposits of very low tensile strength, the weakest place in the pile is on its flank and not at the main central plug. By the orthodox view, therefore, the new crater, the main one for the succeeding period of activity, should have a different location from that of the earlier main crater. The fact is, that, in very many cases, the main vent is located at the same place through the many different periods of activity of the greater cones. The beautiful symmetry of a Fujiyama or of a Mayon is the result. The removal of the plug at the close of a dormant period is clearly not the

mere mechanical result of explosion. There must be a preliminary weakening of the plug, and apparently the only cause for that weakening is to be found in the fluxing by juvenile gas.

First we may consider the case where the terrestrial forces keep the liquid column supported in the conduit. With the formation of the plug, the loss of heat falls to a very low rate as compared with that ruling in the active period. Until the plug is removed, nearly all the

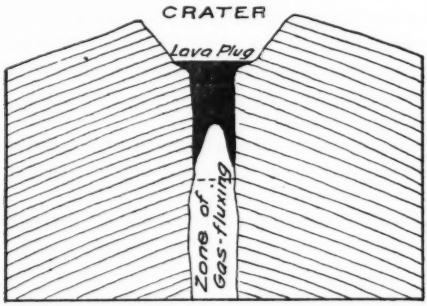


FIGURE 9. Section of upper part of a dormant cone, showing some progress in gas-fluxing. Broken line in middle of vent shows original depth of the solid plug.

loss is due to conduction and is very slow. Two-phase convection is slowed down, but the rise of bubbles does not cease nor does the volcanic furnace cease working, since a renewed concentration of juvenile gas is begun. To that positive source of heat in the conduit is to be added the heat developed by the compression of the gas as it accumulates beneath the plug and as it is squeezed by any upthrusting of the magmatic column due to crustal movement. Gradually the lowest part of the plug becomes liquefied, preferably along its vertical axis, where the heat inherited from the last active period preserves the line of maximum temperature in the whole upper part of the volcano. The reliquefied lava sinks into the column, dissolving some of the accumulating gas, so that heat of solution is probably to be added to the other supplies which tend to threaten the existence of the plug. Hence, at least three processes coöperate in fusing the plug ; these are : heat of chemical reaction, heat of gas compression, and heat of gas solution. As the plug is thus weakened, the gas-tension increases and activity is renewed by one or more major explosions, shattering the remaining part of the plug. (Figure 9.)

Though full experimental data for the testing of these conclusions are not yet in hand, it is not difficult to see that the fluxing power of even small masses of juvenile gas is great under these conditions. If chemical reactions supply any large fraction of the heat lost by radiation in the active period, they must raise the temperature of the lava column under conditions of dormancy. This involves a slow melting of the country-rock, and especially the plug.

In most cases dormancy is ended by explosions so powerful as to show pressures under the plugs of even higher order than the pressures in the greatest modern cannon at the moment of discharge. These pressures run well over 2,000 atmospheres. If a given plug, when frozen to maximum thickness, is 1000 meters deep, the initial pressure on the gas first collecting beneath it would be about 270 atmospheres. Amagat's experiments furnish the data from which the temperature effect of the adiabatic compression of the typical gases, carbon dioxide and hydrogen, may be approximately computed.

At the request of the writer Professor H. N. Davis has kindly deduced the thermodynamic equation for these two cases. If T_0 is the initial temperature; T, the final temperature; p_0, the initial pressure; and p, the final pressure, we have

$$T = T_0 \left(\frac{p}{p_0}\right)^n,$$

in which n is an exponent approximately determined from Amagat's curves. If the initial temperature and pressure are, respectively, 1273°C. absolute and 270 atmospheres, and the final pressure is 2700 atmospheres, the average value of n for carbon dioxide is about 0.17; and, for hydrogen, n probably lies between 0.26 and 0.31. For carbon dioxide the computed value of T is 1880° absolute, and for hydrogen 2300° to 2600° absolute. This adiabatic compression of carbon dioxide would develop heat to the amount of about 200 calories per gram. Similar compression of pure hydrogen would develop an amount of heat ranging from 3000 to 4000 calories per gram. The compression of the gaseous mixture actually formed under volcanic plugs would produce heat to amounts intermediate between those calculated for carbon dioxide and for hydrogen. Since hydrogen is one of the most abundant constituents of the mixture, it is possible that adiabatic compression of the mixture, under the conditions above described, would produce at least 1000 calories per gram of gas. Since the latent heat of holocrystalline igneous rock is about 90 calories (Vogt), this heat of compression could fuse more than 10 grams of rock per gram of gas.

Calculation further shows that if the compression of a considerable volume of gas be isothermal, other conditions being as above assumed for the adiabatic compression, the heat produced is of the same large order of magnitude.

As the lower part of the plug is fused, the liquid sinks through the gas-rich part of the magma column, so that the fluxing gas is always in immediate contact with the solid rock. Since the solid plug retains a relatively high temperature inherited from the last active period, and since the vertical axis of the plug is the hottest part of the volcanic cone at all levels above the top of the lava column, it is clear that fluxing will be most rapid along the axis.

Again, a local development of heat is to be expected as the re-fused rock, which had been largely freed of gas in the last active period, begins to absorb the gases collecting in the conduit. Nothing is known as to the solution heat of any juvenile gas as it is absorbed in a natural magma. In each case it is practically certain to be positive and it may be important in amount. The data for the same gases when dissolved in water have some value in the way of analogy. The following table is taken from Thomsen's Thermochemistry:

Vapor or gas dissolved in water.	Heat of solution. For 1 gram-mol.	For 1 gram.
NH_3	8,430 cals.	496 cals.
SO_2	7,700	120
Cl_2	4,870	69
CO_2	5,880	134
H_2S	4,560	134
HCl	17,315	475

When hydrogen dissolves in water, heat to the amount of about 800 cals. per gram of the gas is evolved.[42]

In this whole problem it must be remembered that hydrogen forms a relatively large part of juvenile gas-mixtures. This gas has the highest specific heat of all substances yet measured, and its heat of solution in water is also very high. Its efficiency in melting a volcanic plug may perhaps be greater than that of the other gases and vapors put together.

In view of all the conditions, it seems correct to hold that the accumulation of gas beneath a solid volcanic plug develops a special kind of local furnace. The energy here transformed into heat is both potential and mechanical. In part, it is heat of solution; in large part, it

[42] G. N. Lewis, verbal communication.

may be due to chemical reactions; in part, it is due to the condensation of free gas constantly increasing in mass, within a closed chamber. The increase in mass is assumed to be due to the exclusion of gas in the crystallization at the walls of the abyssal injection, and perhaps to other molecular transformations within the magma chamber.

If the lava column is not kept supported, but withdraws for a time from the plug, the compression-melting of the plug must await sufficient accumulation of gas from beneath or the return of the fluid lava (because of general strains in the earth's crust or for other reasons) into the conduit. The mechanism is, however, the same as in the case just discussed, and the base of the plug is gradually melted.

The re-fused magma must become gradually more and more charged with gas. How much gas per unit weight of rock would be required to fuse an average plug is obviously now impossible to declare, but the maximum quantity of gas in solution may not need to be more than two or three per cent of the total weight of the magma in the actual conduit. The astounding explosive energy of newly awakened volcanoes, as shown in the vast heights to which fine ejecta are thrown and by the excessive comminution of the respective plugs, seem to indicate saturation of the magmas to an even higher degree. The "evisceration" of some cones has possibly been due to the concentration of juvenile gases beneath plugs not yet sufficiently fluxed to permit of a reopening of the former vents by more moderate explosions. In neither case, however, is it probable that pure explosion could restore activity to the dormant volcanoes. Here again, as in the continuance of activity after the vent is opened, the problem is one of heat supply.

Another cause for dormancy is to be found in the sudden emptying of a lava-filled conduit by escape through a lateral fissure, forming satellitic intrusion, or distant surface flow, or both at once. This is a common event at both Kilauea and Mauna Loa. A multiple effect is produced. A large volume of specially concentrated juvenile gas is taken out of the vent, just so far diminishing the motive power and heat supply in that vent. As observed at Kilauea, the level of the conduit lava may not be restored to its former height for months or years. During that time the upper part of the conduit wall is cooling, and, through decrepitation and initial weakness, large masses fall from the wall and choke the vent. A resumption of activity at the surface must be delayed by these processes.

In the present argument we need not dwell on the fact that, if the volcanic mechanism is nicely balanced, a minute effect, like tidal strain, may pull the trigger and renew activity, for which the essential conditions have been long preparing. However, it seems clear that cos-

mical stresses do not seriously deform an abyssal injection during its lifetime as the feeder of a central vent. During such a period, which may be thousands of years in length but seldom or never millions of years in length, crustal readjustments must be minute, for even the greatest lava flows that could have been thus squeezed out at central vents are always very small in relative measure. The last-mentioned fact and the persistent recurrence of eruption at the main vent appear to forbid the hypothesis that renewal of activity at central vents is due to *renewal* of injection along new abyssal fissures. It would be highly improbable that the vent of a second injection would coincide with that of the first injection; and on the other hand, the great crustal disturbance accompanying the second injection should normally cause first-class lava floods at the initial vent, instead of the comparatively insignificant flows actually observed at central vents. Difficult as the problem is, the change from dormancy to activity does not, in general, seem to call for anything so drastic as a strong deformation of the earth's crust in its entire thickness.

In conclusion, the gas-fluxing hypothesis appears to be worthy of a leading place among those which can be constructed to account for the stubborn persistence in the revival of activity at a vent like Mokuaweoweo, Vesuvius, or Etna.

Small Size of Central Vents.

The gas-fluxing hypothesis accounts for other general features of central eruptions. The small cross-sections of the vents at Kilauea, Hualalai, Mauna Loa, and even at Mokuaweoweo, as everywhere else in the world, are all of the order of size expected if the fluidity of each lava column is due to the slow passage of relatively minute masses of gas through those vents.

The writer is not able to agree with J. D. Dana, that the conduits beneath Kilauea and Mauna Loa are nearly equivalent in horizontal section to the great sinks ("calderas") in which the lava lakes are situated. Each of those sinks measures roughly five kilometers by three kilometers. The periodic rise and fall of the floor of the Kilauean sink (the only one carefully studied) can be explained on the assumption that its conduit has a much smaller cross-section. The "New Lake" after five years of activity, was emptied in 1886, and was proved to have had a depth of only a few meters. It was a saucer-shaped sheet of lava resting on solid rock. (Compare Plate III.) When the present Halemaumau is emptied, the lava runs out through a very narrow hole apparently less than thirty meters wide, and leaves a broad, funnel-shaped cavity. The action is like that of water running out of a domestic sink

with centrally placed discharge; in both cases vortical motion is observed in the rapidly escaping liquid.[43] Similarly, the vast Kilauean lake of 1820 to 1860 is best interpreted as a true lake with solid floor, except for the narrow pipe which has always supplied the heat at this volcano. That pipe is probably the same pipe into which Halemaumau at times discharges its lava and from which the gas issues, to make the fountains of "Old Faithful." All the Kilauean lakes have represented *overflows* from that vent or from a few, more temporary, narrow pipes. The fluidity of the lake has, in each case, been preserved for years by the process above outlined for the existing lake.

Whatever adverse criticism of this conclusion regarding Kilauea may succeed, it is certain that the whole area of either of the Hawaiian sinks cannot be directly taken to represent the size of the conduits. The surface areas of other lava columns active in historic time are all very much smaller. It is doubtful that any one of them, just below the floor of the flaring crater, has been as much as one kilometer. J. D. Dana computed the volume of the 1852 floor from Mauna Loa, which appears to have emptied the conduit to a depth of 2,500 feet, as estimated from the difference of level of the summit lake and of the point of discharge. The result was 10,560,000,000 cubic feet.[44] This corresponds to the volume in a cylindrical conduit about 2,300 feet or 700 meters in diameter. Similar calculations from other lateral outflows seem to give a mean diameter for the conduit of the same order of magnitude. Such a lateral fissure once opened, it would seem highly probable that the conduit would be emptied almost entirely by the simple outflow of the lava through the fissure; discharge into "subterranean cavities," would be unlikely. Moreover, it is possible that some of the 1852 lava represents a temporary rise of magma in the conduit, so that only part of the estimated volume of the flow can be used in calculating the average diameter of the Mauna Loa conduit. Thus, the calculation made according to the method outlined, strengthens the suspicion that the lava column of the world's vastest volcano is but a comparatively narrow pipe, perhaps much less than 600 meters in average diameter.

All of the ancient central vents now exposed as "necks" after prolonged denudation, are relatively small. (Compare Figure 10.) The average diameter of the pipes recorded in geological literature is well under 500 meters. The largest of the hundreds of deeply eroded lava necks in the Mount Taylor region of New Mexico is said to be not more

[43] C. H. Hitchcock, Hawaii and its Volcanoes, Honolulu, 1909, p. 254.
[44] J. D. Dana, Characteristics of Volcanoes, New York, 1891, p. 240.

than 450 meters in diameter. The size of the lava conduit is often not shown by the maps of many volcanic "necks." For example, the largest Scottish "necks" described by Geikie are chiefly composed of pyroclastic materials and may represent erosion sections through explosion funnels with their characteristic flare. Without even allowing for

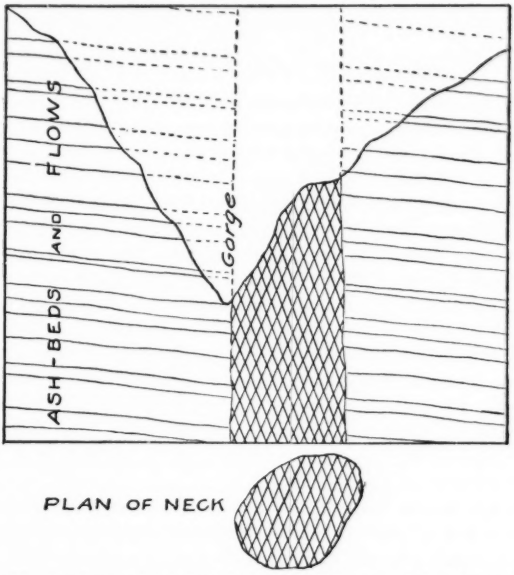


FIGURE 10. Section and ground plan of basalt-lava neck in a lateral gorge of the Iao valley in West Maui, illustrating the cylindrical form due to gas-fluxing. This was one of the subsidiary vents on the flanks of the great West Maui cone. There is no trace of faulting in the ash-and-flow series and it is possible that this neck represents the local enlargement (by gas-fluxing) of one of the dike fissures now visible in the canyon. Nearly natural scale; major diameter of the neck about 50 meters.

that uncertainty, the writer believes that the conduits of central eruptions, measured below the explosion zone, have an average diameter of much less than one kilometer. The term "conduit" here means, of course, the pipe above the primary abyssal injection. The main magma chamber may be indefinitely greater in horizontal section.

We may conclude that the conduits of central eruptions are always small and of the order of magnitude appropriate to the gas-fluxing

hypothesis. On any other hypothesis it is hard to explain the fact that the pipes of moderately large cones are about as large as those of the very greatest cones. In all cases there seems to be a *limital size* and that is controlled by the available heat supply along the axis of the vent. The size is small because the (indirect) fusing power of emanating gas must be strictly limited. Moreover, the cylindrical shape of each typical pipe is a solutional or fluxing form. (Figure 10.)

Explosive types: Magmatic and Phreatic.

The foregoing genetic statement for the Hawaiian vents has been sketched in terms of a quite general process and it is necessary to glance at the relation of the hypothesis to the explosive type of central eruption.

Volatile matter occurring in the rocks of the contact-shell about any intrusive magma must show increased tension. If the intrusion is large and near enough to the earth's surface, this tension may lead to explosion in the roof of the igneous body. In case no incandescent matter is extruded, the explosion is not volcanic according to our definition of that term (p. 48). Following Suess, it may be called *phreatic.* A similar explosion may happen as a result of the slow conduction of heat from the conduit of a long dormant volcanic cone. Such a cone is normally porous. Rain-water, snow-water, or sea-water is trapped in the vesicular flows and loose tuffs, as these are in turn buried during the original growth of the cone. The circulation of vadose water is also facilitated by this special porosity.

The suggestion of Suess that the remarkable explosion at the famous Rieskessel was of phreatic origin has been supported by the detailed studies of Branco and others.[45] Purely geological studies had indicated the presence of a large laccolithic mass beneath the great Ries depression. That conclusion has been brilliantly supported by the magnetic studies of Haussmann in the region. The local disturbances of the needle in dip and azimuth can be explained, according to Haussmann, only by the assumption of one or more large subterranean bodies of basic rock.[46] In the Rieskessel itself the upper surface of the basic rock is calculated to be no more than two kilometers deep. Outside the depression, its average depth was estimated at five kilometers. Since the visible floor of the Ries is the granite of the " Grundgebirge,"

[45] W. Branco, Abhand. kön. preuss. Akad. Wiss. Berlin, 1902, p. 14.

[46] K. Haussmann, Abhand. kön. preuss. Akad. Wiss. Berlin, 1904, Abt. IV, p. 137. Sauer has suggested that the liparite of the Kieskessel tuffs is due to the melting of the intruded granite by the basic magma. See W. Branco and F. Fraas, Abhand. kön. preuss. Akad. Wiss. Berlin, 1901, p. 54.

the basic mass or masses can only be interpreted as due to injection. Branco dates the intrusion of the Ries "laccolith" in the mid-Miocene. The overlying granite and its Mesozoic sedimentary veneer were domed by the injection and the top of the dome was largely destroyed by a phreatic explosion. It was followed by the appearance of a little liparitic tuff erupted at a few points in the newly formed basin, but the explosion itself was non-volcanic.

According to Sekiya and Kikuchi, the great explosion of 1888 at Bandai-San was absolutely unaccompanied by the extrusion of lava.[47] A priest living on the mountain survived the explosion. He reported the vapors surrounding him to have been respirable, and the Japanese geologists conclude from all available data that the catastrophe was a steam explosion. There were no signs that juvenile gases formed an important part of the volatile mixture. This "eruption" of Bandai-San seems, therefore, to be an excellent example of a phreatic explosion *on* a true volcanic cone.

Phreatic eruption means steam-explosion without magmatic extrusion. Kilauea represents magmatic extrusion without steam-explosion. Between these two extremes of terrestrial activity stands the type representing the vast majority of active and extinct central eruptions. In the non-volcanic or pseudo-volcanic activity of Bandai-San in 1888, as in a Kilauea or a Vesuvius, true igneous injection is a pre-requisite. The gases given off at Kilauea form a nearly pure juvenile mixture with characteristic high temperature. The gases given off at Vesuvius form a mixture of juvenile, resurgent, and vadose volatile matter. A type of the resurgent gas is the carbon dioxide set free in the demonstrable assimilation of Mesozoic limestone and dolomite in the Vesuvian lava column. The gas and vapor given off at Bandai-San in 1888 was apparently almost purely vadose or meteoric in origin.

True volcanoes of the central-eruption type must vary enormously in the relative and absolute proportions of juvenile, resurgent, and vadose fluids composing their emanations. As the resurgent and vadose fluids are volatilized, heat is lost and the viscosity of the lava column rises. Assimilation of foreign rock in depth must lower the temperature, and in the end, increase the viscosity and also the average violence of explosions. In addition, magmatic differentiation generally brings the more silicious and more viscous pole to the upper part of the lava column, and aids in the preparation of explosive conditions.

For these and other reasons, volcanoes of the central-eruption type

[47] S. Sekiya and J. Kikuchi, Jour. Coll. Science, Tokio, 1889, p. 106.

have always had a great variety in dynamic habit and in the character of their ejectamenta. Yet, in every one of them, the essential problem is the same; it refers to the mechanism by which heat is kept supplied to the narrow, thread-like vents for long periods. To that problem, the questions as to how sea-water or vadose water is absorbed by underground magma, as to the dominance or subdominance of steam-explosion at individual vents, and as to the physical differences in the emanating lavas, are subsidiary. The problem of the Hawaiian vents is, from this point of view, the problem of all vulcanism reduced to its lowest terms. Here the gas-fluxing hypothesis seems satisfactory. In most other volcanic regions, where thick sediments are cut by the feeding magma, or where heavy snows or rains wet the cones and, through seepage, cause steam-explosions, the control by juvenile gas may be obscured to the eye of the observer, but it still remains, in every case, the true cause of continued activity. Kilauea and Mokuaweoweo, like Matavanu and the vents in Réunion, teach us that steam-explosion is an adventitious feature of vulcanism. Except abyssal injection itself, the only indispensable process in central vents is *quiet exhalation.* Neither explosive drilling of the vent, nor ejection of lava, nor the contacting of meteoric or marine water with hot lava is indispensable. Each of these three processes is an expected effect of the slow emanation of juvenile gas from main abyssal injections or from their satellitic offshoots.

Magmatic Differentiation at Central Vents.

The chemical variation exhibited in the lavas or pyroclastic materials successively ejected at the normal vent offers a problem of special importance. Volume for volume, this variability is much more striking than it is in the average large intrusive body — stock, batholith, laccolith, or sheet. At present many petrologists favor the pure-differentiation theory, which regards the splitting magma as primary, and finds no place for notable assimilation of wall-rocks by the primary magma. The writer believes that this question can only be cleared up by an attentive study of the world's plutonic masses, and that, in the nature of the case, its answer is not to be found at central vents. Field and chemical relations point indubitably to the fact that wholesale assimilation has occurred in the subjacent bodies classed as stocks and batholiths. Because of assimilation these masses generally have not the basaltic composition of the primary abyssal injection. The visible granite, diorite, or syenite represents the frozen top of an abyssal injection which is there a more or less differentiated syntectic. The lower part of each injection, approaching the substratum level, is prob-

ably basaltic and little modified in composition from its original condition. The syntectic-differentiation theory is so strong that the writer is disposed to prophesy its ultimate victory in the competition among explanations of the igneous magmas and rocks.

Since the lava column of every volcanic vent is an offshoot from an abyssal injection, the lava may represent either the primary basalt, or one of its differentiates, or syntectic material, or a differentiate from syntectic material. The rapid chemical variations in the extrusive magma at the average central vent shows that the conditions are here

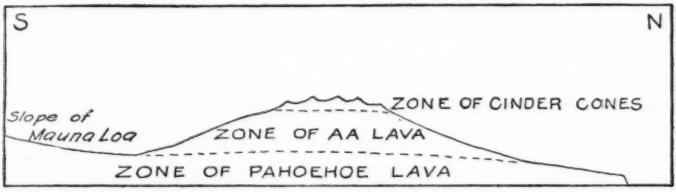


FIGURE 11. Diagrammatic projection of Mauna Kea, illustrating the field character of the rocks encountered in climbing from sea-level to the summit at 4213 meters above sea. Length of section 55 kilometers. Vertical scale twice the natural.

specially favorable for differentiation. Two of these conditions are implied in the essential mechanism of central eruption. The upward passage of juvenile and resurgent gases in great relative abundance, lowers the "point" of solidification of the magma, increases the fluidity, and probably in still other ways aids in magmatic splitting. Secondly, the alternation of active and dormant periods means that the top of the lava column passes repeatedly through the narrow range of temperature (just above the crystallization point), where differentiation is most likely to take place.[48] High superheat is opposed to magmatic splitting.

Each of these conditions affects only a small volume of magma at any one time; if lava representing either pole of the differentiation is alone extruded, the volume of that flow must be relatively small. New magma rises in the vent. It may be mixed with that representing the other pole of the differentiation just accomplished. The mixture may be extruded, or it may itself be differentiated before the next outflow. Through absorption of foreign rock the new lava may have a composition unlike that originally differentiated.

It seems inevitable, therefore, that, at the restless volcanic vent, the ever-changing conditions must make a cone which is chemically heter-

[48] Intrusive masses normally pass through this temperature range only once before solidification.

ogeneous to an extent not matched in the usual plutonic mass. Standard examples have been described at Electric Peak and Sepulchre Mountain in the Yellowstone Park; at the Lipari Island vents; at Tonopah, Nevada; at the Kaiserstuhl in Baden, etc.

The extinct Mauna Kea in Hawaii (alt. 4213 meters) affords a good illustration of a lava column which has not contacted with important sedimentary masses. In this case magmatic differentiation seems to have played the most important rôle, though its heavy winter snow-cap may have furnished a special condition for explosiveness in the last stage of the cone's activity. (Figure 11.) The broad base of this volcano, visible in the long sea-cliff on the north side of the island, is essentially composed of olivine basalt of the fluent pahoehoe type. From about the 1500-meter contour to the 3500-meter contour, the slopes are chiefly underlain by flows of a much less femic basalt, with some interbedded ash and breccia. Above the 3500-meter contour the mass is very largely pyroclastic, and the leading petrographic types are trachydolerite and andesitic basalt or basic augite andesite. (Plate IV, B.) The following analyses show the march of the differentiation:

	1	2	3
SiO_2	49.19	49.73	50.92
TiO_2	1.72	3.05	2.55
Al_2O_3	14.02	16.39	17.59
Fe_2O_3	5.62	7.58	3.80
FeO	8.68	3.98	6.69
MnO	.54	.23	.20
MgO	6.42	4.06	3.90
CaO	9.10	7.17	6.97
Na_2O	3.24	4.12	4.28
K_2O	1.04	1.93	1.86
H_2O-	.74	.81	.35
H_2O+		.54	.79
P_2O_5	.28	.84	.40
CO_2		None	None
NiO		.04	"
Cr_2O_3		None	"
BaO		.03	
SrO		None	
ZrO_2		.03	
S		None	
SO_3		"	
	100.59	100.53	100.30
Sp.gr.	——	2.911	2.761

1. Average analysis of twenty olivine basalts from Hawaii, representing closely the composition of the basement of Mauna Kea.
2. Andesitic basalt, flow at 11,000-foot contour, Mauna Kea.
3. Trachydolerite, flow at 13,000-foot contour, Mauna Kea.

Analyses 2 and 3 by G. Steiger in the laboratory of the United States Geological Survey.

Progress in Explosiveness at the Greater Vents.

The explosive effect at central vents is a function of the magmatic viscosity and of gas tension, which means gas concentration.

Though the presence of much gas tends to lower the viscosity, temperature is obviously in dominant control over that property of magma. The initial store of heat in the abyssal injection is normally lost through radiation in the crater, through conduction at the roof and walls of the whole magma chamber, through assimilation of country-rock, and possibly through the absorption of vadose water. As the whole mass cools, the juvenile gas emanates with ever lowering temperature and the lava of the volcanic conduit must have a slow decrease of average temperature.

Magmatic differentiation must tend to affect the viscosity of the upper zone of lava, the exploding zone, in the same sense. The more acid differentiate usually rises toward the top of the vent. Though differentiation may be roughly cyclical, the successive splitting tends to make a secular increase of acidity in the upper zone of the conduit magma. Hence, irrespective of temperature, there is an increase of viscosity in the magma zone where explosions originate. The case of Mauna Kea, just described, is an example of the partial control by magmatic differentiation over explosiveness. As the viscosity rises, the escape of magmatic gases is more difficult; the resulting tension is periodically relieved by explosions. Here also the action is cyclical, but there is, on the average, a slow increase in the amount of gas trapped before each explosion.

Again, the amount of volatile matter entering the magma column, either through assimilation of sediments or through the direct absorption of meteoric water, tends to increase with process of time. And, with the growth of a great, generally porous cone, the chance for phreatic explosion at or near the crater is favored.

All of these factors *work together* to produce maximum explosiveness at central vents which are long-lived because fed from great abyssal injections. The maximum normally appears in an advanced stage in the evolution of a first-class volcanic cone, though necessarily some

time before complete extinction. Short-lived vents, opened above satellitic and therefore relatively small injections, will, of course, have no such tendency to great systematic change in explosiveness.

Lava Outflow at Central Vents.

A noteworthy feature of all central eruptions is the relatively insignificant size of their individual lava flows. Thoroddsen has estimated the volume of the celebrated fissure eruption of Skaptar Jökull in Iceland at 12,320 millions of cubic meters. He gives the volume of one prehistoric flow as 43,160 millions of cubic meters; of a second, 500,000 millions of cubic meters. In striking contrast are the following examples of the larger recorded flows at volcanic cones.

Locality.	Date.	Volume in millions of cubic meters.	Authority.
Semeroe, Java	1885	300	De Lapparent.
Etna	1669	980	von Waltershausen.
"	1852	420	"
"	1865	92	"
"	1879	57	"
Mauna Loa, Hawaii	1852	299	J. D. Dana.
" "	1855	455	C. H. Hitchcock.
" "	1880–1	413	" "
" "	1907	153	E. D. Baldwin.

Geological investigation shows that the flows from the central vents of Paleozoic and later periods have been of the same order of magnitude as the flows of the human period. With very few exceptions or none at all, these larger flows have issued from lateral fissures in the cones, and a large part of the volume of each flow is readily explained as the lava drained out, hydrostatically, from the upper part of each conduit. Without recorded exception all overflows at the main craters are incomparably smaller than those noted in the foregoing table. Therefore, the ascensive force in central conduits is either slight, or, if powerful, is applied for short periods.

The smallness of individual overflows clearly suggests that the magma chambers which continue to feed central vents are very seldom deformed by important movements of the earth's crust. If the magma in the chamber were diastrophically pinched, we should expect, at times, relatively enormous lava-floods from central vents. Some authors hold, on the contrary, that the growth of a great cone sometimes occasions subsidence, so that crustal movement may be a consequence rather than a direct cause of lava overflow at central vents.

Without entering further into this subject, it will here suffice to mention the principal causes for lava outflow as deduced from the abyssal-injection premise. These are:

1. Very minute deformation of the feeding magma chamber.

2. The effervescence of lava, due to the periodic accumulation of magmatic gases in the vent. These gases may be juvenile or resurgent.

3. The assimilation of country-rock in depth, leading, probably, to increase of volume.

4. The increase of volume through heating in the conduit "furnace" — a process specially like to occur during the dormant period when the vent is temporarily plugged.

These causes may co-operate, but at basaltic volcanoes the third is clearly subordinate.

The Two Types of Lava Flows.

A preliminary study of the Hawaiian lavas, with respect to their field habit, has led the writer to suspect significant gas-control even in this detail of vulcanism. On the average the vesiculation of pahoehoe or ropy lava was found to be more evenly developed than in the aa or block lava. The contrast is illustrated in Plate V. The rather uniformly disseminated vesicles of pahoehoe are of relatively small and relatively uniform size, and tend to have spherical form. The irregularly distributed vesicles of aa lava are generally larger, though more variable in size; much fewer in number, and of less total volume per unit volume of rock; and more irregular in shape. These facts indicate a more uniform distribution of gas in the pahoehoe than in the aa type. The aa vesicle, which is often thousands of times bigger than the average pahoehoe vesicle, has undoubtedly grown through the coalescence of many bubbles of gas. Such growth must in very high degree (see page 78) favor the escape of the gas into the air, and we may regard these large vesicles as representing so much gas trapped in the freezing lava. Before solidification had set in, gas must have escaped from every aa flow in large volume. In fact, observers of the two types in actual movement agree that the gas emanation from flowing aa lava is much more abundant than that from flowing pahoehoe.[49]

The difference of field habit in fluent lava and block lava is thus explained, with some show of probability, by the relative abundance of

[49] Cf. J. D. Dana, Characteristics of Volcanoes, New York, 1891, p. 242. Judge Hitchcock describes a typical Hawaiian aa flow as advancing "with no explosions, but a tremendous roaring, like ten thousand blast-furnaces all at work at once."

volatile matter and, still more, by the evenness of its distribution. For both reasons pahoehoe lava is certain to be less viscous than is aa lava, other conditions being the same; the pahoehoe moves, as it were, on molecular and vesicular "ball-bearings."

The fact that many flows, from the very points of emission, are altogether of the one type, while others are throughout of the other type, shows that the differences of gas-distribution are developed in the vent. The problem as to exactly what circumstances there control the gas-distribution has not yet been solved. Slight differences in temperature, or differences in the advance toward solidification (with gas expulsion) may be the effective cause. The writer has observed a tendency for the phenocrysts of aa lava to be of larger average size than those in pahoehoe lava which gives practically the same oxide proportions in ordinary chemical analysis (volatile matter other than water neglected); but he is as yet not prepared to regard this as an established rule.

Vulcanism Originating in Satellitic Injections.

We have so far considered central vents as, in general, direct offshoots of main abyssal injections. The latter have been described: as dike-like, though often of great widths; as extending upwards from the primary substratum, nearly or quite to the earth's surface for some such vertical distance as forty kilometers. Batholiths have been interpreted as chemically modified abyssal injections of the primary basalt. Plutonic stocks and bosses represent cupolas in batholithic roofs. Stocks, bosses, and batholiths compose the group of "subjacent" intrusive bodies.[50] Laccoliths, sheets, and ordinary dikes are individualized bodies, satellitic with respect to their feeding abyssal injections, and like the latter, owe their intrusion to a simple parting of the invaded rock-formations. Irregular bodies intruded in the same fashion have been called "chonoliths"; they form a fourth class of "satellitic injections."[51]

All satellitic injections soon lose thermal and hydrostatic connection with their respective abyssal injections. All laccoliths and chonoliths, like most sheets and some dikes, have solid floors during most of their magmatic activity. If a satellitic injection is of large size, its content of heat energy and of gas may suffice to open one or more vents to the earth's surface, according to the methods already described. Volcanic action is thus initiated which differs in some respects from that due to direct emanations from a main abyssal injection.

[50] R. A. Daly, Journal of Geology, **13**, 508 (1905).
[51] Cf. Journal of Geology, **13**, 498 (1905).

The importance of this fact is manifold. Its recognition aids in our understanding: the short life of many volcanoes of the central type; the lack of lava flows at many of them; the independent activity of neighboring vents; the chemical dissimilarity of the lavas from neighboring vents; the quite common clustering of many small vents in a region which shows no trace, or but few traces, of the alignment of its volcanoes; and the frequent evidence of surface deformation in such regions. The evidences for this type of vulcanism are indirect, but they are numerous; taken together, they form a combination of no mean strength.

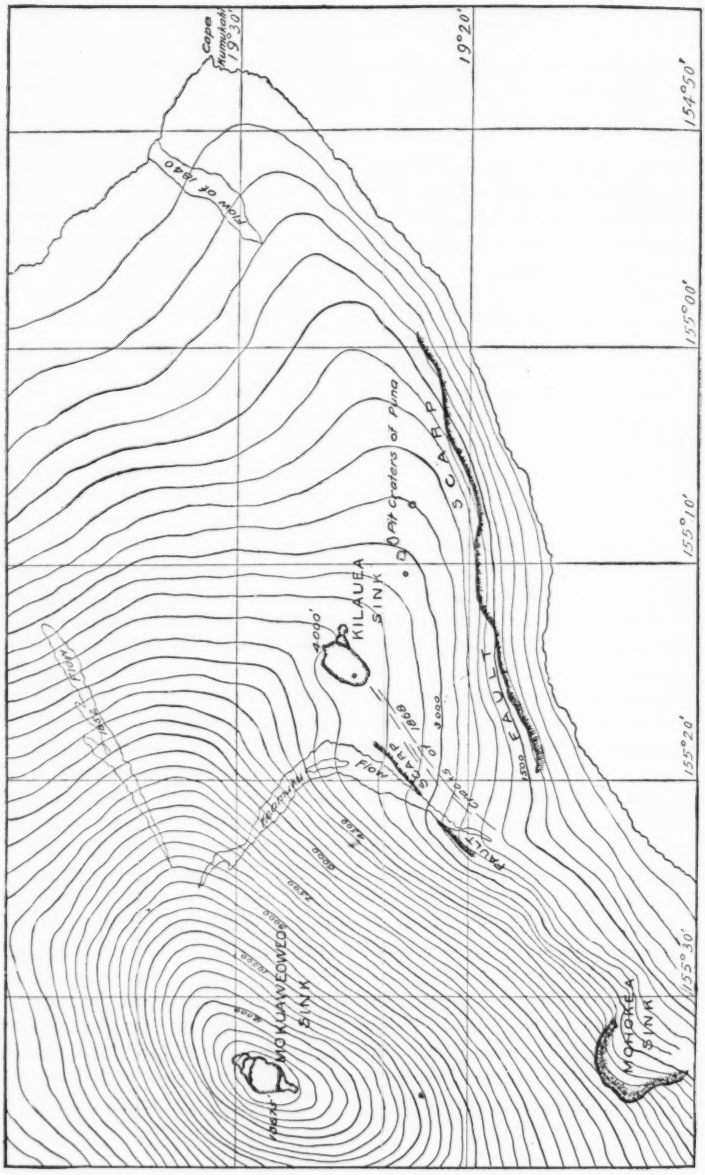
In the first place, an excellent analogy to the vents from satellitic injections can be observed in nature. The blow-holes and driblet cones formed on the surface of the deep lava flows of Etna, Réunion, Hawaii, Savaii, etc., are continued in their brief activity because of the thermo-gaseous energy of lava quite removed from the parent vent. The blow-holes occasionally opened in the dome-shaped "bulges" or "tumuli" formed on the pahoehoe of Hawaii or Réunion are particularly instructive, for such tumuli, when just formed, represent small laccoliths of still fluid lava capped by recently frozen lava-crust.

To the weight of analogy is to be added that of a priori reasoning. According to almost any of the extant theories of igneous action, vulcanism originating in magmatic satellites should be *expected*. Many satellitic injections of great size have been exposed by erosion; it would be a matter for distinct surprise if none of them ever perforated its roof.

Field observation must naturally make the compelling test of the principle. Have we any active example? Can we find traces of it in denuded regions where erosion enables us to study the anatomy of volcanoes? Each method of applying the field test has its own difficulty. In the first case the satellitic injection is inaccessible and can only be located through inference; in the second case it is but rarely that denudation could expose the injected mass without destroying the conduit above. Yet the writer believes that the field inferences seem to support the principle.

The case of Kilauea, as an illustration, will be presented in some detail; the conception was first clearly attained by the writer during his field-work at that volcano in 1909.

Kilauea, the Vent of a Satellitic Injection. — A glance at the government map of the island of Hawaii shows the reader that the contour lines are peculiarly shaped in the southeast quarter of the island. (Figure 12.) From a low depression a few kilometers west of Kilauea to Cape Kumukahi, a distance of fifty kilometers, the lines are rather


Cape Kumukahi 19°30'
19°20'
154°50'
155°00'
155°10'
155°20'
155°30'
Flow of 1840
KILAUEA SINK
Pit Craters of Puna
SCARP
FAULT
Flow
Flow
Flow

strongly convex to the eastward. They there portray a long arch-shaped spur running out from Mauna Loa. From sea-level at the cape, the crest-line of the spur rises at the average rate of about twenty meters per kilometer, or 1 in 50. At Kilauea the spur is plateau-like, and immediately to the westward of the Kilauean "sink" there is a faint downward slope to the west. This arrangement of slopes does not mean that Kilauea is a crater surrounding a cone. It is rather a large pit or "sink" in the side of Mauna Loa (Plate II, A). Along the Kau coast, southwest of Kilauea, the Mauna Loa slope varies from 1 in 10 to 1 in 15, averaging about 1 in 12.

The broad spur is capable of two interpretations. It has either been built up by the specially prolonged extrusion of lava in this region, or it is due to local deformation of the general Mauna Loa slope, as if by deep-seated intrusion of the laccolithic type.

There is no sign that Kilauea has ever overflowed the outer walls of its great sink. The writer tried, in the field, to answer that question definitely by plotting the attitudes of the festoons of "ropes" on the pahoehoe flows forming the surrounding surface, but was defeated, through the failure to find a sufficient amount of that surface not covered by ash deposits. In any case, however, the general topography shows that no significant part of the spur could have been built up by overflows from this vent. Lava seems never to have issued from most of the many pit-craters situated on the back of the spur, and the total effect of activity of that kind at the other craters in the whole Puna district may have been a vanishing quantity so far as the development of the arch is concerned.

On the other hand, it is evident that lava flows from the upper slopes of Mauna Loa could not have constructed the spur in its present form. Such flows as do run down the southeast flank of the main volcano are deflected by the arch and run either northeastwardly toward Hilo, or southwardly into southern Kau. Finally, the spur does not appear to owe its principal volume to a succession of fissure eruptions along its axis. The flow of 1840 may be an exception tending to prove the rule. It represented a subterranean discharge of the magma chamber of which Kilauea is still the active vent. The formation of that chamber is really the point at issue. The injection of its magma might have followed or directly caused the formation of the spur; in either case extrusion of lava from the chamber is a wholly subsidiary and unessential fact. Further field work is necessary to determine how far the surface of the spur has been raised by local eruptions like that of 1840.

The alternative explanation of the spur-arch regards it as a mass of

Mauna Loa lava uplifted by a geologically recent intrusion of magma which is still fluid. The form of the arch suggests a laccolithic body. Though there is, perhaps, no possibility of proving it, this hypothesis has high value in giving a new explanation for the general independence in the activity of Mokuaweoweo and Halemaumau. The feeding channels of a typical laccolith are always narrow. They must freeze quickly and the satellitic injection loses hydrostatic connection with its parent abyssal injection. The latter may most simply be regarded as that underlying Mokuaweoweo now and during the building

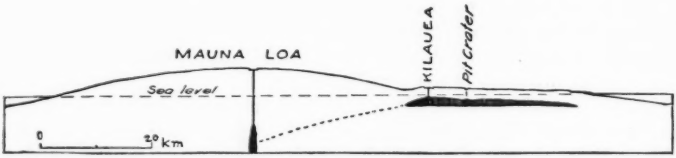


FIGURE 13. Diagrammatic section to illustrate the hypothesis that the Kilauean vent is fed from a large, still partly fluid laccolith injected into the side of Mauna Loa. The broken line represents the now sealed channel through which the laccolithic magma was injected; its course merely conjectural. Natural scale.

of most or all of the island of Hawaii. In other words, the postulated laccolith is an offshoot from the main Pacific fissure which located the Hawaiian archipelago. (Figure 13.)

The remaining evidences favoring this hypothesis may be briefly listed.

1. The many pit-craters in the eastern Kau district and in the Puna district, including Kilauea, Kilauea Iki, Keanakakoi, Mokaopuohi, etc., are almost unique features in the whole island. (Plate IV, A.) Some of the pits on Hualalai are of similar form and their mode of origin may possibly be connected with another satellitic injection beneath that western cone. The pit-craters of Kau and Puna are not arranged in lines, as if located on master fissures, but are irregularly grouped in clusters. The field evidences show that most, perhaps all, of them have not been opened by explosion, and also that most of them have not emitted lava. The extinct ones, like the active Halemaumau, have been kept open by fusing gases. Their lives have been brief, because dependent upon temporary concentration of juvenile gases at the various points. In origin they are analogous to the clustered blow-holes on the crust of the Kilauean lake between 1820 and 1840.

2. The Kilauean records show that, from 1820 to 1911, that crater

has been decreasing in its activity with fair regularity. The very rapid rate of decline suggests a relatively small feeding chamber.

3. The imperfect observations so far made seem to show that the lava fountains of Mokuaweoweo more nearly approach brilliant-white heat than do those of Kilauea in the hottest state of its present eruption. The difference of temperature may be as much as 200°C.[52] Assuming that the magma of the Kilauean laccolith originally had the higher of these temperatures, the cooling would be of the order expected if the laccolith were of good size and not more than a few thousand years old.

If the average slope of Mauna Loa, before the laccolith was injected, was one in twelve, as now in southern Kau (obviously an uncertain assumption), a minimum estimate of the volume of the laccolith may be made. The top of the broad arch just east of Kilauea must have been raised at least 1000 meters, which is, therefore, the minimum thickness of the laccolith in that large area. The average thickness, as shown by the surface deformation, would be at least 500 meters and the area at least 500 square kilometers. The corresponding volume of the laccolith is 250 cubic kilometers. A body of magma of that size and endowed originally with the high temperature demonstrated at Mokuaweoweo, might, in part, remain fluid for 2000 years. There is nothing to indicate that Kilauea is so old.

Clearly little stress is due any such computation of the size. It can give only an order of magnitude. The magmatic body may be much larger, and it may have a form not ideally laccolithic.

4. Kilauea is the largest, the last, and most persistent of all the pit-craters for some good reason. The shape of the arch on which it stands suggests that it overlies the highest point in the roof of the laccolith, where the fluxing gases would naturally accumulate in largest quantity and where they would finally tend to emanate from the magma chamber. The smaller, extinct craters may easily represent so many points where irregularities in the roof, lower down, temporarily caused local accumulations of the gases.

5. Like the pit-craters, important systems of earthquake cracks like those of 1868 southwest of Kilauea, are concentrated in the Kau-Puna

[52] Quite recently Dr. Tempest Anderson has recorded that, even in daylight, the lava of the active Matavanu lava lake in Samoa was, at the time of his visit in 1909, of brilliant-white incandescence (Quart. Jour. Geol. Soc. London, **66**, 627 and 632, 1910). This indicates a temperature little, if anything, short of 1400° C. The color of the hottest lava at the "Old Faithful" fountains of Kilauea of the same year was, in the daytime, a bright orange, corresponding to a temperature not far from 1200° C. The intensity of the heat at Matavanu has been, for years, of the order represented in the great eruptions of Mauna Loa.

region of the island. (Figure 14.) This fact is explicable on the laccolithic hypothesis for the origin of Kilauea, since the roof of such a body must evidently be in danger of fissuring and of moderate dislocation.

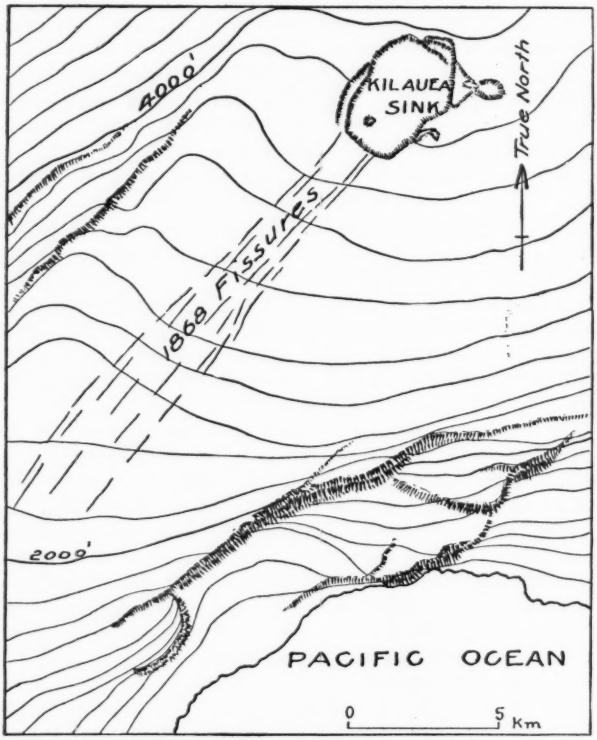


FIGURE 14. Redraft of the Government MS. map (1907) of part of southern Hawaii, showing fault-scarps and "earthquake" fissures. The long scarp in the south ranges up to 500 meters in height. Contour interval, 200 feet.

6. An obvious test of the hypothesis consists in the search for direct evidences of uplift in the laccolithic area. No notices of strongly elevated shore-lines in this region have been published. In view of the considerable number of good observers who have traversed this part of

the coastal belt, it is probable that neither old strands nor coral deposits are here to be found at any notable heights above sea-level. However, that fact, however fully demonstrated, could not invalidate the laccolithic hypothesis. Highly fluid laccoliths like that at Shonkin Sag do not disturb the strata into which they are thrust, to a greater distance from the edge of each laccolith than that equal to one-twentieth or one-tenth of the laccolith's horizontal diameter. Even for more viscous intrusions, like that at the classic Mt. Hillers in the Henry Mountains, this distance is less than one-fifth of the diameter. There is no sure reason for thinking that the edge of the Kilauea laccolith was near enough to the seashore of the pre-intrusion period to displace the coast-line materially. It is also important to observe that a fault runs roughly parallel to the longer axis of the great arch for a distance of about thirty-five kilometers. It is located from three to five kilometers inside the shore-line. Its downthrow throughout is on the seaward side, and the amount of throw varies from about 100 meters to 500 meters or more. (See Figures 12 and 14.)

The maximum displacement is registered in a remarkable cliff south of Kilauea. (Figure 14.) This greatest of all the pure fault-scarps in the island finds its own explanation, if we correlate the displacement with the upthrust incidental to the laccolithic injection.

7. The generally accepted hypothesis that Kilauea is a primary vent like Mokuaweoweo, entirely fails to explain the fact that we have no certain trace of a lava outflow over the wall of Kilauea. It places no difficulty in the way of the hypothesis here outlined.

8. Nevertheless, it is significant that, while Kilauea is less violent in its eruption than Mokuaweoweo, the lower vent is the more continuously active. The latter contrast finds simple explanation on the laccolithic hypothesis, which implies that the magma chamber of Kilauea, below the cylindrical vent, is much nearer the earth's surface than is the vaster magma chamber feeding the long pipe of Mokuaweoweo. The longer pipe is evidently liable to the more ready discharge by eruption through lateral fissures, and the space voided by such a discharge must, on the average, be greater than that voided in a discharge of Kilauea. A minute subsidence of the laccolith's nearly flat roof after a major discharge at Kilauea would be much more rapid than a similar settling of the thick roof over the main, probably narrower and more fissure-like chamber beneath Mokuaweoweo.

9. Finally, the laccolith has been imagined with the help of an actual example. Under the Uwekahuna triangulation station in the wall of the Kilauean sink, the writer found a small, but typical laccolith which arches the basaltic flows above it, and rests on older flat-lying

flows. (Figure 15.) This body, shown in complete section, is only about 150 meters long by 18 meters in thickness in the middle, thickest part. Its roof, still essentially unaffected by erosion, is little more than 140 meters thick. The rock of this small body is holocrystalline, wehrlitic in chemical composition, but having enough plagioclase to place it among the ultrabasic olivine gabbros. The body shows chilled contact phases and its injected origin cannot be questioned. We have here,

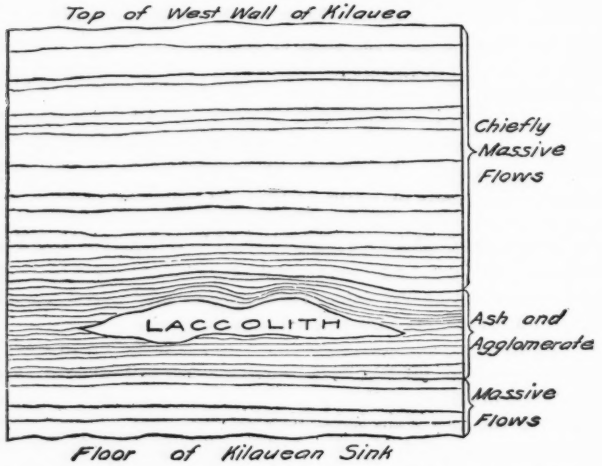


FIGURE 15. Diagrammatic view of wall of Kilauea at the Uwekahuna station, showing ultra-basic porphyritic gabbro injected into older volcanic layers. The "laccolith," arching the ash-beds above it, is about 150 meters in length. About natural scale.

barring volcanic perforation of the roof, a true homologue of the laccolith postulated to explain the peculiar history and relations of Kilauea.

In summary, we note the convergence of several independent lines of argument in favor of the suggested hypothesis. It seems justifiable to class Kilauea tentatively as the living vent of a still liquid satellitic injection. We may also conclude that it is unsafe to deny, simply because of the hydrostatic independence of the two active Hawaiian lava columns, that a primary fluid substratum of basaltic composition underlies the whole island.

An Icelandic Example. — Reck has suggested that the crater of the Hrossaborg in central Iceland is a gas-exploded opening (diatreme) in

the roof of a laccolith. The injection is of comparatively late date, presumably Recent or Quaternary.[53]

We may now briefly note other probable examples of the opening of vents above satellitic injections. Testimony to its existence in former geological periods and in other regions tends to strengthen belief in the hypothesis as imagined in this Hawaiian study.

Tertiary and Older Vents from Satellitic Injections. Suabian and Scottish Examples. — As a result of his extraordinarily thorough study of the mid-Miocene eruptions in Suabia, Branco concluded that the Urach region is underlain by a "kuchenförmige Masse," or laccolith. In ground-plan its estimated diameters range between thirty and forty-five kilometers. Its position coincides with that of a very low, but broad doming of the Jurassic strata in the Bavarian Alb, as determined by Regelmann. Through secular erosion, the frontal escarpment of the Alb has retreated at least twenty-three kilometers since the volcanic epoch.

On the top of the Alb plateau are thirty-eight tuff vents; in the escarpment are thirty-five more, and in the "Vorland," or region traversed by the escarpment in its southward retreat, there are fifty-four tuff vents and five basaltic vents. No lava flows occurred on the Alb, and the few lava necks have become visible because of denudation in the "Vorland." Though the explosion funnels are still more or less intact on the Alb, the largest of them, the Randeck "Maar," does not exceed one kilometer in diameter. The average diameter of the 132 vents is far less. The evidence is clear as to the short life of each of these vents, which Branco has made the world type of "volcanic embryos." Their brief, almost wholly explosive activities, their distribution in a cluster without reference to master fractures, and the dome-like warping of the Jurassic beds in this region, all declare the justice of Branco's laccolithic hypothesis. Furthermore, his discussion of Mandelsloh's 340–meter boring at Neuffen shows that the temperature gradient in at least one part of the Urach region is abnormally high, about ten meters per degree Centigrade. Branco regards the abnormal gradient as due to the wave of heat still being conducted from the mid-Miocene injection. This suggestion is by no means extreme and it clearly tends to support his laccolithic hypothesis.[54] (See also p. 100.)

The peculiar abundance of small tuff-necks of Permian age in parts of Scotland is subject to a similar tentative explanation. Various memoirs of A. Geikie have made these vents famous as types of true

[53] H. Reck, Monatsber. deut. geol. Ges. No. 4, 1910, p. 293.

[54] W. Branco, Schwaben's 125 Vulkan-Embryonen, Stuttgart, 1894. Cf. E. Suess, Das Antlitz der Erde, Bd. 3, 2te Hälfe, 1909, p. 655.

necks. In Fifeshire, eighty of them have been counted in an area measuring eighteen kilometers by ten kilometers. In western Ayrshire, sixty vents are found in an area measuring sixty by thirty kilometers, and, of those vents, twenty are necks occurring within an area of thirty-five square kilometers. In the great majority of cases, Geikie and his collaborators have been unable to find any connection between the positions of the necks and lines of dislocation. The Carboniferous strata have suffered sieve-like perforation like that of the Jurassic beds in Suabia. In each of the Scottish districts, the lower part of the very thick Carboniferous sedimentary series carries numerous thick sills of dolerite. These sills are mapped as chiefly Carboniferous in date, but Geikie thinks that some of the Fifeshire sills at least are Permian. The steady association of tuff-neck and sill in the Scottish shires scarcely looks accidental.

Gas emanations from the magma forming these actual intrusives or similar ones occurring in the underlying pre-Carboniferous formations, together with the possible emanation of gas from the heated country-rock, would seem to be competent to explain most of the tuff-necks. Explosive drilling (diatremes) and gas-fluxing might in turn dominate in the opening of the vents. The total activity must be small, because each gas-emitting or lava-emitting chamber was small.

The list of districts where the writer suspects secondary vulcanism includes also the area of necks in Noss Sound, Shetland.[55] These are small and the volcanic throats are filled with a coarse agglomerate of sandstone and shale. Peach and Horne infer that the vents never emitted any streams of lava.[56] The eruptivity is referred to the Lower Old Red Sandstone period. The date may be nearly the same as that of the injection or the thick sills and dikes which abound in the Noss Sound region.

A Necessary Division of Central Vents. — It is obviously difficult to devise field criteria which shall infallibly distinguish central eruptions respectively originating in main abyssal injections and in satellitic injections. Long and strong activity, large outflow of lava, and alignment in chains will generally characterize the central vents of abyssal injections. Brief activity, small output of lava, cluster grouping, and traces of surface deformation in the region are the expected features of the central vents of satellitic injections. As one or more of these features is absent or is obscured, the classification is hard to apply.

[55] A. Geikie, Quart. Jour. Geol. Soc. London. Presidential Address, **48**, 95 (1892).

[56] B. N. Peach and J. Horne, Trans. Roy. Soc. Edinburgh, **32**, 359 (1884), and **28**, 418 (1878).

The chief object of the foregoing discussion has been, however, not to propose a division directly useful in field work, so much as to erect a fence over which speculation about the earth's interior cannot pass. The best way to check mischievous speculation is to advance beneficent speculation, founded on all the known facts. For example, the bold statement that there can be no magmatic substratum beneath a district bearing two simultaneously active lava columns of differing heights can no longer be made without an investigation of their nature as "principal" vents (abyssal injections) or "subordinate" vents (satellitic injections). The formal classification is of positive use in recognizing a mechanism by which the petrographic contrast of the lavas from neighboring vents may have originated. If two of these are opened above different satellitic injections, the chances are good that the magmatic histories of the injections will be different; their emanating lavas would diverge in chemical type according to the progress respectively made in the formation of syntectic and differentiated magmas.

Some "subordinate" vents are monogenetic in Stübel's sense, and there are a few analogies between the system of vulcanism here suggested and that elaborated by the illustrious German. But the writer cannot agree with Stübel's principal conclusion as to the motor power in vulcanism, and entirely fails to find geologic or petrologic evidence for the existence of his "Panzerdecke."

General Summary.

The general hypothesis briefly outlined in the present paper assumes, by sanction of the facts of general geology, that the earth is exteriorly composed of successive shells of density increasing with depth. Beneath the interrupted sedimentary shell is a continuous solid "granitic" shell, and still deeper, an *eruptible basaltic shell or substratum.* All igneous action, since an early pre-Cambrian period, is the result of the mechanical intrusion of the substratum basalt into the overlying shell. This fundamental process is specifically called "*abyssal injection.*" It is not a hypothetical process, but one which is clearly apparent in the chemistry and field relations of igneous rocks. The conditions leading to abyssal injection form a subject of great theoretical difficulty, but the discovery of the exact mechanism is not essential to the presented explanation of volcanoes. Nor is it necessary to decide on the degree of viscosity characterizing the basaltic substratum, although it is pointed out, once again, that the observed small amount of deformation of this planet under cosmical stresses does not prove

that the substratum is crystallized. The central thesis of this paper is that all vulcanism is a consequence of abyssal injection, or in other words, that from the date of the oldest known pre-Cambrian lavas, every volcanic vent has been opened because of a preliminary *mechanical intrusion of molten basalt* into the *acid earth-shell.*

Emphasis is laid on the absolute necessity of classifying the gases and vapors which do important work at volcanic vents. These are either magmatic or phreatic in origin. The *magmatic* volatile fluids are subdivided into *juvenile* and "*resurgent*"; the *phreatic* fluids into *vadose* and *connate.* Each of these classes may be important in the dynamics of volcanic explosion; on the other hand, the juvenile magmatic gases are assuredly the most important in keeping a volcanic vent alive.

Besides fissure eruptions and central eruptions, the writer recognizes a class of vents not usually considered in treatises on vulcanism. This third kind of volcanic action may be called *foundering eruption;* the hypothesis is presented that some batholiths have swallowed up parts of their roofs, thus directly exposing a large area of each batholith to the sky.

This paper is chiefly concerned with the problem of central eruptions. They are of two main classes. In the "*principal*" class, each vent represents emanations from a main abyssal injection; in the other, "*subordinate,*" class, each vent originates over a magmatic body (laccolith, sheet, etc.) which is satellitic with respect to a main abyssal injection. Of these two classes, "principal" volcanoes must, on the average, be the more intense in activity, of longer life, more productive of lava-flows, and more clearly related to crustal fissures. The facts of the field suggest that Kilauea is a "subordinate" volcano. Tertiary and Paleozoic examples are probably represented in Suabia and Scotland. The localization of central vents and their very common alignment are explained by the principle of abyssal injection. Lack of alignment in a group of vents is suggestive of their "subordinate" origin. In the nature of the case, "subordinate" vents must, in their activities, show a high degree of *independence* of one another and of neighboring "principal" vents.

Continued eruption at a central vent is a heat problem. The primary heat of its abyssal injection is not the only source of thermal supply. A leading place in the theory should be kept for the supply due to chemical reactions among the primary constituents of the injected magma. Abyssal injection means an enormous change in the pressure conditions of the magma. As a result, the juvenile gases rise toward the top of the magma chamber. They are concentrated in the

actual volcanic pipe and, according to the law of mass-action, exothermic reactions on a large scale are to be expected. The possibility that energy was potentialized in the primitive basaltic substratum by the formation of dissolved endothermic compounds, like cyanogen, ozone, hydrogen peroxide, etc., is indicated. In consequence of changes in pressure and temperature, due to injection, the dissociation of those compounds and the formation of new, stable compounds formed partly or wholly from their elements, give a double source of heat in the magmatic column. The heats of formation for the probable reactions are so great that small masses of juvenile gas might furnish a relatively large supply of heat. Though it is at present impossible to estimate the fraction of the total volcanic heat due to chemical reactions, a working philosophy of vulcanism should give due regard to the hypothesis that a central vent is a *true furnace.*

Using Siegl's recent results from experiments, the writer has calculated the approximate rate of heat loss through radiation at an active crater. The loss by radiation occurs, in general, at a much faster rate than the heat loss by conduction into the walls of the vent for a depth of many kilometers. The methods of the transfer of heat from the depths are discussed.

The principle of "*two-phase convection*" is concluded to be essential to the maintenance of prolonged activity at central vents. This conception is illustrated by the analogy of solid spheres moving, under gravity, in viscous fluids.

Explanation is offered for the dormancy and related periodicity of certain vents; for the typical shape of such a vent, and for its comparatively small size. These features, when coupled with long persistence in activity, are chiefly dependent on two-phase convection. Since the latter process is, in its turn, dependent on the rise of gases in the magma chamber, this general conception of central eruptions is called the *gas-fluxing hypothesis.*

The petrographic variety of lavas is to be largely explained on principles which have been demonstrated in plutonic geology. The lavas emitted at central vents may be: primary basalt; differentiates of pure primary basalt; syntectic magmas, i. e. those produced by the solution of foreign rock in primary basalt; or differentiates of syntectic magmas. The petrographic diversity in the lavas of neighboring volcanoes becomes better understood through the recognition of the two ("principal" and "subordinate") classes of central vents.

The explosiveness of volcanoes is a necessary step in the march of events following abyssal injection. The inciting cause is to be sought in the tension of resurgent gas as well as of juvenile gas. Progress in

magmatic differentiation tends to favor explosiveness to an important degree. Magmatic and phreatic explosions must be distinguished if the tangle of vulcanological facts is to be unravelled. Though the rise of hot magma into rocks charged with vadose or connate water does often cause explosion, the steam-pressure produced by such volatilized water can no more be regarded as the cause of vulcanism than is the boiling of a kettle the cause of the heat in the stove. The formation of the magma column, extending through the earth's "granitic" and sedimentary shells to the surface, is the crucial problem. It is obviously a mere matter of detail whether or not the country-rocks at the upper end of the magmatic column are wet and therefore explosive.

The facts of volcanic geology seem, therefore, to co-operate with the facts of plutonic geology in showing that the essential process in igneous action on this planet is the rise of basaltic magma from the universal substratum along abyssal fissures in the earth's acid shell. The whole group of conceptions emphasized in this paper may be summarized in the name "*substratum-injection hypothesis.*"

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PLATE I.

A. Panoramic photograph of Halemaumau on January 13, 1910, with Mauna Loa in the background. The nearly circular lake was about 200 meters in diameter; its surface was estimated to be about 25 meters below the rim of the crater. Copyright by E. Moses, Hilo.

B. Panoramic photograph of Halemaumau on February 20, 1910. Lake level fallen about 30 meters below the surface of the "black ledge" in the foreground. Copyright by E. Moses, Hilo.

PLATE I, A.

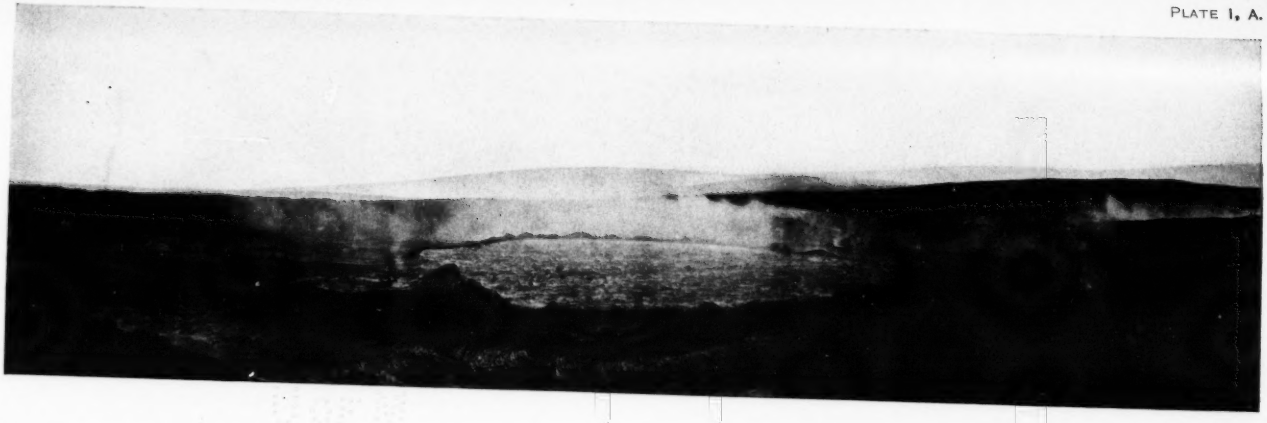


PLATE I, B.

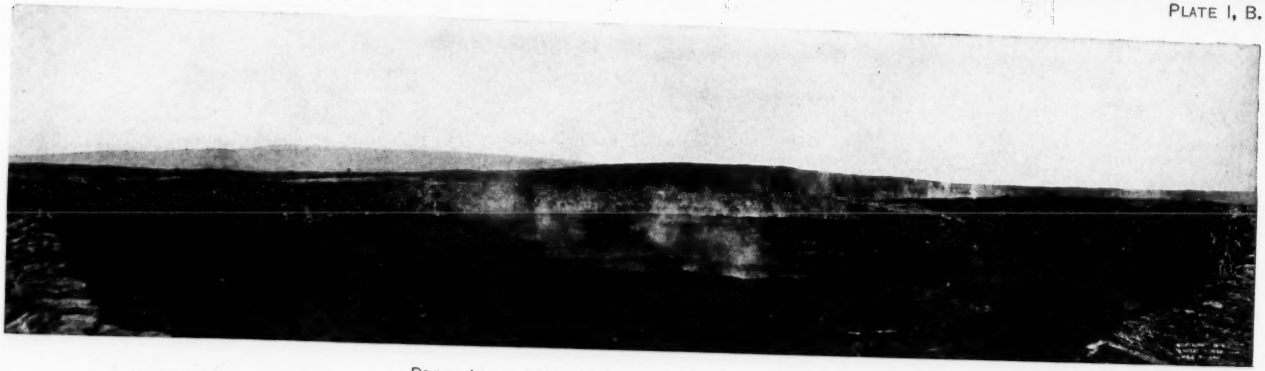


PLATE II.

A. Halemaumau, the crater in the Kilauean sink, taken from the Uwekahuna triangulation station by H. E. Wilson, Aug. 29, 1908. Diameter of crater about 500 meters.

B. The lava lake at Kilauea, taken at night (July, 1909) with an exposure of somewhat less than one quarter of a second, showing an outburst of "Old Faithful," an intensely luminous cave in the background, and a few of the brighter cracks in the "scum" on the lake.

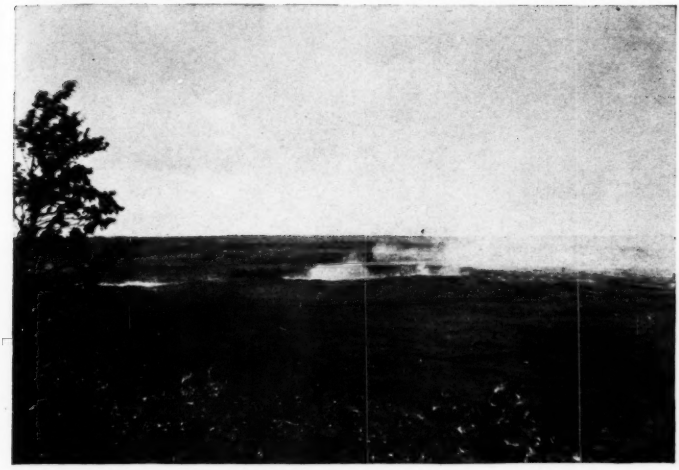


PLATE II, B

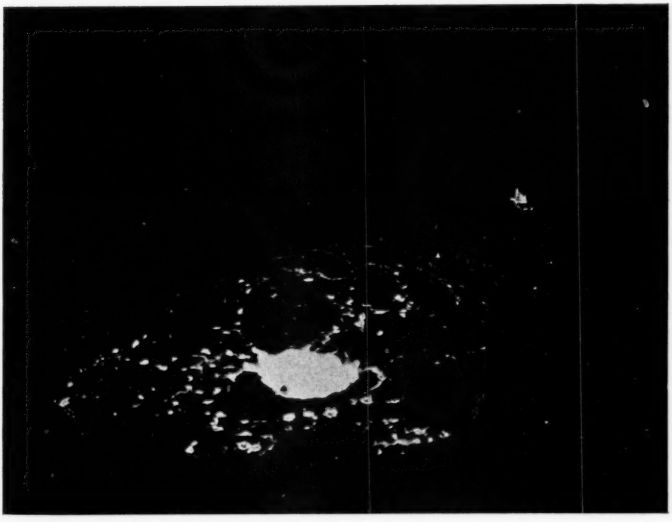


PLATE III.

The largest of the Puna pit-craters in Hawaii. The plain is a frozen lava lake, the bottom of which is indicated by the inked line. Beneath that massive lava is old talus material, exposed in the fault-scarp of the foreground, which shows a maximum thickness of 60 meters for the lava prism. The conduit which fed this lake was probably at the deep hole overlooked by the fault cliff of the middle foreground. The lava plain is about one kilometer in length.

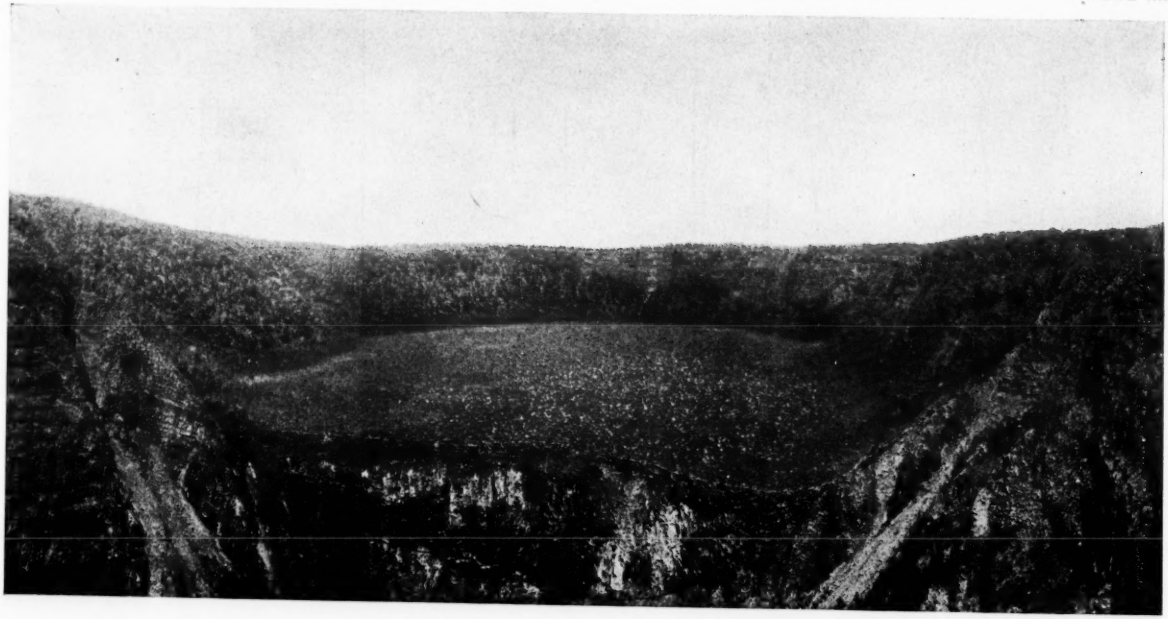


PLATE IV.

A. One of the small pit-craters of the Puna district of Hawaii. It is a pipe fluxed through the old, flat-lying lava of the Mauna Loa (fluent) type. The crater is about 175 meters in diameter.

B. Cinder cones from 100 to 200 meters or more in height, from summit of the highest cinder cone on Mauna Kea, looking northeast.

PLATE IV, B

PLATE V.

A. Typical pahoehoe lava of Hawaii. About four-fifths natural size.

B. A common phase of the aa lava of Hawaii. About four-fifths natural size.

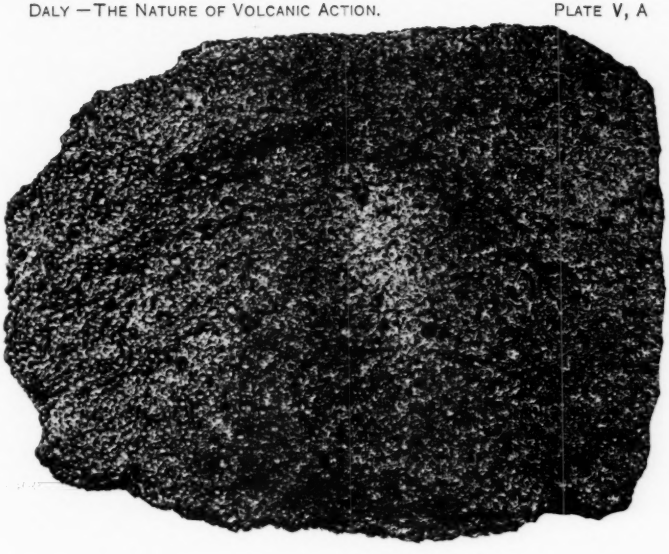
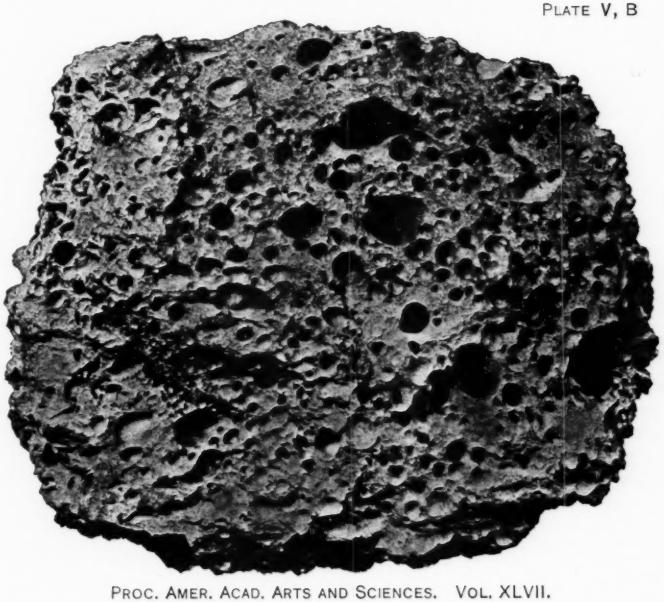


PLATE V, B



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Mrau